TRAFFIC-RESPONSIVE STRATEGIES FOR PERSONAL-COMPUTER-BASED TRAFFIC SIGNAL CONTROL SYSTEMS

By

JOHN ZENYOUNG LUH

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

1989

ACKNOWLEDGMENTS

One of the pleasures of finishing the dissertation is thanking the people who contributed to it. My gratitude cannot be adequately expressed to the Florida Department of Transportation, which sponsored this research as part of the traffic signal retiming project, nor to the University of Florida, which provided financial support during the entire four years of my study.

I have profited greatly from the suggestions and assistance given by the members of my supervisory committee. I am eternally grateful to them.

Professor Kenneth G. Courage has been my advisor since I first arrived in Gainesville. I have obtained tremendous benefits from his professional competence and vast practical experience in traffic signal control. His honoring me by chairing my supervisory committee and his enthusiastic support have given me opportunities that otherwise would have been impossible.

Dr. Charles E. Wallace, Director of the Transportation Research Center and McTrans Center, has been my employer for over three years. My primary duties under him have been associated with the technical and software maintenance for the FHWA's Highway Capacity Software. From him, I learned what high professionalism is. His commitment to excellence is evident in every piece of my work.

Dr. Chung-Yee Lee has helped me far beyond simply being a member of the committee. He assisted me during the entire course of this study. He asked inspirational questions, offered helpful suggestions, and criticized the draft of the dissertation. Without his invaluable time and effort in assisting me, this study would have been impossible.

Dr. Joseph A. Wattleworth has encouraged me like a good friend over the past four years. He has also been a source of inspiration and motivation. I enjoyed his classes and obtained most of my knowledge of freeway operation modeling and highway safety analysis from him.

Dr. Mark Chao-Keun Yang served as the outside member of the committee. He assisted me in the development of mathematical models in this research. His knowledge of probability and his sometimes perplexing questions have allowed me to grow intellectually.

Discussions with my colleagues, Lawrence T. Hagen and Charles D. Jacks, always helped me get around problems encountered with this research.

Special appreciation is due to Mr. Thomas R. Sawallis, an instructor at the University of Florida Writing Center, for his professional work in editing this dissertation.

I am indebted to my wife, Tracy, for her advice, her support, and her understanding. Finally, I would like to dedicate this dissertation to my dear parents.

TABLE OF CONTENTS

		Page
ACKNOWLEDGMENTS		ii
LIST OF TABLES		vi
LIST OF FIGURES		vii
ABSTRACT		ix
CHAPTERS		
ONE	INTRODUCTION	1
	Background	1
	Objectives and Scope	5
	Organization	7
TWO	LITERATURE REVIEW	9
	Signal Performance Evaluation	9
	Decision Between Coordination and Free Operations	19
	Exploration of Personal-Computer-Based Signal Systems	21
THREE	ANALYTICAL METHOD FOR PERFORMANCE EVALUATION OF SEMI-ACTUATED SIGNALS AT LOW VOLUMES	27
	Introduction	27
	Assumptions and Notations	27
	Method Development	32
	Isolated Control	39
	Coordinated Control	50
	Test of the Analytical Method	57
	Comparison with a Pretimed Model	60
	Summary and Discussions	65
	Equations Development	66
FOUR	APPROXIMATION METHOD FOR PERFORMANCE EVALUATION OF SEMI-ACTUATED SIGNALS AT LOW VOLUMES	79
	Introduction	79
	Concept of the Method	80
	Method Development	81
	Tests of the Approximation Method	88
	Summary and Discussions	92

Page

FIVE DECISION BETWEEN COORDINATION AND FREE OPERATION 95

Introduction 95
Decision Making Process 96
The DELVACS Program 100
Case Studies 104
Application on PC-Based Signal Control Systems 117

SIX CONCLUSIONS AND RECOMMENDATIONS 122

Conclusions 123
Recommendations 126

BIBLIOGRAPHY 131

BIOGRAPHICAL SKETCH 136

LIST OF TABLES

TABLE		Page
3.1	Patterns (in Terms of Red and Green Times) and Their Probabilities at a Three-Phase Semi-Actuated Signal Under Isolated Control	45
3.2	Patterns (in Terms of Red and Green Times) and Their Probabilities at a Three-Phase Semi-Actuated Signal Under Coordinated Control	55
3.3	A Further Comparison Between the Analytical Method and the Pretimed Model Method	64
5.1	Measures of Effectiveness and Performance Indices Under Coordinated Control in Case 1	108
5.2	Measures of Effectiveness and Performance Indices Under Isolated Control in Case 1	109
5.3	Measures of Effectiveness and Performance Indices Under Coordinated Control in Case 2	110
5.4	Measures of Effectiveness and Performance Indices Under Isolated Control in Case 2	111
5.5	Desirable Operations in the Two cases of the Example	112

LIST OF FIGURES

FIGURE		Page
2.1	Basic Configuration of Urban Traffic Control Systems	22
2.2	Basic Configuration of PC-Based Traffic Signal Control Systems	24
3.1	Block Diagram of the Analytical Method	34
3.2	Stop Probability and Average Delay Equations and the Conditions for Their Use Under the Analytical Method	37
3.3	Transitions, Red Times, and Transition Probabilities at a Three-Phase Semi-Actuated Signal Under Isolated Control	41
3.4	Example of the Determination of Pattern Probability	49
3.5	Transitions, Red Times, and Transition Probabilities at a Three-Phase Semi-Actuated Signal Under Coordinated Control	52
3.6	Stop Probability and Average Delay Comparisons, the Analytical Method vs. Simulation	61
3.7	Stop Probability and Average Delay Comparisons, the Analytical Method vs. the Pretimed Model Method	63
3.8	Actuated Signal Operation Examples of Single Ring without Overlap and Dual Ring with Overlap	67
3.9	Queue Length Example at a Signalized Intersection	76
4.1	Determining the Total Effective Red Time and the Number of Green Occurrences	84
4.2	Stop Probability and Average Delay Equations and the Conditions for Their Use Under the Approximation Method	89
4.3	Stop Probability and Average Delay Comparisons, the Approximation Method vs. Simulation	91
4.4	Stop Probability and Average Delay Comparisons, the Approximation Method vs. the Analytical Method	93

FIGURE Page

5.1 Block Diagram of the Decision Making Process 98

5.2 Flow Chart of the DELVACS Program 101

5.3 Artery Layout, Phase Sequences, and Timing Settings of the Example 105

5.4 Traffic Flow Rates in Cases 1 and 2 of the Example 107

5.5 Intersection Layout, Phase Sequence, and Timing Setting of the Switching Condition Example 114

5.6 The Switching Thresholds of Total Intersection Volume for the Example Intersection with a Two-Phase Semi-Actuated Signal 116

Abstract of Dissertation Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Doctor of Philosophy

TRAFFIC-RESPONSIVE STRATEGIES FOR
PERSONAL-COMPUTER-BASED TRAFFIC SIGNAL SYSTEMS

By

John Zenyoung Luh

May, 1989

Chairman: Kenneth G. Courage
Major Department: Civil Engineering

Traffic on the artery generally moves more smoothly during peak periods if signals in proximity are coordinated. During off-peak periods when traffic is light, however, free operations may be more efficient than coordination from the standpoint of system performance. The change from coordination to free operation (and vice versa) is a typical traffic-responsive problem, but the choice between them is often subjective, since the literature offers very few methods for the decision.

This dissertation proposes a decision making process whereby traffic engineers can make more effective choices on light traffic signal operations, based on system performance in terms of vehicular delay and number of stops. Two methods are developed to supply models needed for evaluating semi-actuated signals at low volumes, under both coordinated and isolated controls.

The decision making process has been implemented as the DELVACS program. A hypothetical example is given to demonstrate the application of the process using DELVACS. The possible approaches for implementing the process on personal-computer-based signal control systems are explored. The advantages and disadvantages of the approaches are discussed, and the resolutions to the potential problems are proposed.

The decision making process provides a viable tool in traffic-responsive controls. The process and the semi-actuated signal evaluation methods developed in this research can also be applied on other types of traffic-responsive signal systems, such as Urban Traffic Control Systems which have been predominant in the United States in the past two decades.

CHAPTER ONE
INTRODUCTION

Background

Traffic-responsive control of signalized intersections represents a significant advance in the traffic control field, and is the subject of extensive research, as well as development efforts. With proper design and operation, traffic-responsive control, which has been in practical operation during the past two decades, can effectively reduce stops, delay, fuel consumption, and emissions. A variety of traffic control techniques in response to traffic demand has been developed, and some have been evaluated in several countries [13, 20, 23, 26]. The underlying philosophy of all the techniques has been to smoothly move traffic with as few obstacles as possible. Coordinating the timing of adjacent signals to allow progressive traffic movements has been recognized as one of the most effective means to achieve this goal.

The need to coordinate adjacent signals varies according to the geographic and traffic environment. The most important factors have been identified as intersection spacing and traffic volumes [7, 59]. For widely spaced intersections, signals usually operate individually because of the small influence on traffic flows from their neighbors. Where signalized intersections in close proximity influence each other's traffic flows, traffic volumes become an important factor in their coordination.

Early thinking on the subject of signal control always indicated the need to interconnect signals into a single system and to work toward maximizing progressive movement during peak periods, though during off-peak hours, free running or flashing control may better handle the traffic [54]. The reason is rather evident. Coordinating the signal timing to allow traffic on the artery to travel smoothly without being stopped at intersections (which is called progression) is often accomplished at the expense of extra delays to the cross street traffic. When the arterial traffic decreases during off-peak periods, the benefits gained on the artery may not offset the losses on cross street traffic. This phenomenon has been observed by Riddle and Hazzard [43]. From a series of simulation and field tests, they concluded that coordination is superior to free operation under all conditions where volumes exceeded 350 vehicles per hour.

These findings suggest that it is preferable for signals in proximity to be coordinated during peak periods. During off-peak periods when traffic is light, however, free operation may be more efficient from the standpoint of system performance. The change from coordination to free operation (and vice versa) is a purely traffic-responsive problem. But the choice between coordination and free operations is often subjective, since the literature offers very few methods for the decision. Developing a method to allow traffic engineers to make more effective choices on light traffic signal operations is the subject of this research.

Asking whether to change from coordination to free operation (or vice versa) is equivalent to asking which operation offers better performance. In other words, the decision rests mainly on the

performance evaluation of the signals within the system under the two alternatives.

A variety of models has been offered to evaluate signal performance. Most of the models available, however, have centered around pretimed signals mainly because their operation is simple. Under pretimed control, the sequence of right-of-way assignments (phases) and the length of time interval for each phase are fixed. Pretimed signals are well suited to coordination operation since progression can be easily maintained.

Unfortunately, the literature offers very few models dealing exclusively with the growing number of actuated signals, since their operation is more complex. Traffic-actuated control attempts to adjust the sequence of phases (through skipping of phases with no traffic demand), and the length of time interval for each phase (through adding extension intervals to the minimum green interval) in response to traffic demand. Traffic-actuated signals can be further classified into two types of operations: (1) full-actuated operation and (2) semi-actuated operation. In full-actuated operation, since each phase is controlled by traffic demand, it is difficult to maintain progression on the artery. Hence, full-actuated signals are seldom used in coordination control. In semi-actuated operation, the designated main street is governed by a non-actuated phase and cross streets by actuated phases. The non-actuated phase has a green light at all times until cross street has traffic demand. Semi-actuated signals are widely used on arterial roadways, since they are able to not only maintain progression on the major street but also provide flexible control to

cross street traffic. In conclusion, semi-actuated signals are the major concern of this research.

A common approach for semi-actuated signal evaluation is to use averages, such as average cycle lengths and green times, in a model for pretimed signals. The use of pretimed models to evaluate semi-actuated signals is reasonable when traffic volumes are moderate to high. In this case, each actuated phase appears in almost every cycle, with phase lengths varying from cycle to cycle. Longer phase length represents heavier traffic demand and shorter represents lighter. Since the average phase length reflects the average traffic demand, the use of its value would represent the average performance.

When traffic is light, however, this method is no longer applicable. In low volume situations, phase skipping (a phase being skipped due to lack of traffic demand) and dwelling (the green light stays on the non-actuated phase waiting for cross street traffic demand) occur frequently. Phase skipping and dwelling make it very difficult to determine the average cycle length and green times. Even though the averages can be determined, as demonstrated in Chapter Three, the models for pretimed phases are no longer valid for actuated phases due to phase skipping and dwelling. Therefore, they cannot be used for semi-actuated signals under low volume conditions.

The lack of a model to evaluate semi-actuated signals under low volume conditions is a critical problem in the decision between coordination and free operations with low traffic volumes. The decision is easier to make when only pretimed signals are involved, since an ample choice of models is available to evaluate their performance. When semi-actuated signals are involved, however, the decision is difficult

due to the lack of appropriate models. Hence, one challenging aspect in considering the choice between coordination and free operations is the development of a model for evaluating semi-actuated signals at low volumes, under both coordinated and isolated controls. The development of such a model is the first task of this research.

The second task of the study is to develop a method to help make the decision between coordination and free operations more effectively. An opportunity for this arose recently when the City of Gainesville, Florida, installed a personal-computer-based signal control system (also called a closed loop signal system by some manufacturers) to supervise the area-wide traffic signals. Both the Florida Department of Transportation and the City of Gainesville have requested the University of Florida to examine the system's operation to pursue better performance. This project was originally initiated for the Gainesville System, and was entitled "Traffic-Responsive Strategies for Personal-Computer-Based Traffic Signal Control Systems." However, it should be noted that the method as well as models developed in this research can also be applied on other types of traffic-responsive signal systems, such as Urban Traffic Control Systems (UTCS) which have been predominant in the United States in the past two decades.

Objectives and Scope

This dissertation presents a methodology for making the choice between coordination and free operations. Two models are developed for evaluating semi-actuated signals under low volume conditions. The first model performs a thorough calculation using probability theory and stochastic processes. The second model uses average values to approximate measures of effectiveness. The first model is referred to

as the Analytical Method and the second as the Approximation Method. A method to make the decision between coordination and free operations is proposed. The application of the method on personal-computer-based signal systems is discussed.

The specific objectives of the research are as follows:

1. Review the literature with respect to signal performance evaluation and the contrast between coordination and free operations.
2. Review the control capabilities of personal-computer-based signal control systems.
3. Develop models to evaluate semi-actuated signals at low volumes, under both isolated and coordinated controls.
4. Propose a method for making the decision between coordination and free operations in response to traffic demand.
5. Discuss the application of the decision making method on personal-computer-based signal systems.

The primary emphasis of this research deals with semi-actuated signals under low volume conditions. The signals have a fixed common cycle length when they are coordinated, but not when run freely. The system of interest is an arterial roadway controlled by semi-actuated signals with light traffic on the cross streets.

The two signal evaluation methods developed in this research have been implemented as two computer programs. The purpose of the two programs is to ease the tedious calculations while demonstrating the feasibility of the two methods. But the program implementing the Approximation Method will be further expanded to the program called DELVACS (Delay Estimation for Low Volume Arterial Control Systems) under

the sponsored project associated with this research work. The DELVACS program implements the proposed method to provide a tool for making choices between coordination and free operations. The DELVACS program is designated to have interface with the Arterial Analysis Package (AAP) [3] to allow the user to run the AAP and DELVACS together, using a common data set.

Since presentation of computer programs is not within the scope of this dissertation, the two programs developed are not intended to represent complete software packages. Nevertheless, they are operational, and can be used immediately within their capabilities.

The two evaluation methods developed in this study are based on existing theories which have been well accepted by the traffic engineering community. The feasibility of the two methods is validated against microscopic simulation. The applicability of the method in deciding between coordination and free operations is discussed.

Organization

The dissertation is organized according to the objectives stated previously. The next chapter reviews literature that is pertinent to this study. The literature search includes traffic signal performance evaluation and the techniques for making the decision between coordination and free operations. Along with the methodology search, a review of the capabilities of personal-computer-based signal systems is included.

Chapter Three presents the Analytical Method to evaluate semi-actuated signals under low volume conditions. The method uses probability theory and stochastic processes to deal with individual cycles. The method produces good estimates, but is complicated to

apply, particularly when signals have more than three phases or have special control capabilities (such as permissive periods).

Chapter Four presents the Approximation Method. The method uses average parameters (such as red and green times). The method offers a cost-effective alternative to the Analytical Method. This is particularly important where conditions are unfavorable to the application of the Analytical Method.

Chapter Five proposes a methodology for making the decision between coordination and free operations. The application of the methodology on personal-computer-based traffic signal control systems is discussed.

Finally in Chapter Six are the conclusions and recommendations emanating from this study. The conclusions include the summary of the findings, and the recommendations suggest the areas for future study.

CHAPTER TWO
LITERATURE REVIEW

The purpose of the literature review is to collect the earlier efforts in order to avoid duplication and stimulate new methodology development. The literature review includes three parts which are pertinent to this study. The first part focuses on the methodologies of traffic signal performance evaluation. The second part reviews the techniques in deciding between coordination and free operations. The last part explores the capabilities of personal-computer-based signal control systems.

Signal Performance Evaluation

Before reviewing the various methodologies, it is necessary to select measures of effectiveness (MOE). The MOEs serve as a basis for signal evaluation, and a variety of MOEs have been used for this purpose. The major ones include delay, number of stops, degree of saturation, excess fuel consumption, and accident rate reduction [54]. Among them, delay and number of stops have been most widely used. The reasons are evident [24]: they can be measured; they are the motorists' major concerns; they have economic worth; and they are easily understood by both technical and non-technical people. The 1985 Highway Capacity Manual (HCM) [19], for instance, uses delay as the sole indicator of level of service at signalized intersections. The TRAffic Network StudY Tool (TRANSYT) [45] and the Traffic SIGnal OPtimization Model (SIGOP) [51] aim at minimizing the combination of delay and number of stops.

Because of extensive use in the traffic engineering community, delay and number of stops were selected as the major MOEs in this study.

Delay and number of stops may be measured directly in the field, or estimated by either simulation or analytical models. A number of methods are available for making the field measurement, such as test-car observations, arrival and departure time recording, and stopped-vehicle count [19, 40]. Field measurement is easy to apply, but is costly and time consuming. It cannot be applied to non-existent situations, such as a projected signal control plan.

Simulation provides a convenient tool for studying delay and number of stops, especially when the real-world system is complex, or when proposed operations are to be evaluated [29]. Experimental conditions can be much better controlled in a simulation than would generally be possible in a field measurement. Simulation also makes it possible to study a system with a long time frame in compressed time, or alternatively to study the detailed workings of a system in expanded time. A number of simulation models are available for signal operation evaluation [4, 18, 31, 44, 45].

But using simulation has disadvantages. Simulation models are often expensive and time-consuming to develop and maintain. Each run of a stochastic simulation model produces only one estimate of a system's true characteristics, and only for a particular set of input parameters, so that several independent runs are required for each set of input parameters, and statistical methods are needed to analyze simulation output data [14]. For this reason, simulation models are generally not as good at optimization as they are at comparing a fixed number of specified alternative system designs [29]. In contrast, an analytical

model, if available, can easily determine the actual characteristics of the system. Thus, an analytical model is generally preferable to a simulation model if such a model can be developed. In other words, analytical models are always of interest.

Pretimed Signal Evaluation

For pretimed signals, a wealth of theoretical analysis models for delay and stops has been offered in the literature [1, 35, 38, 45, 57, 58]. Webster's delay model provided the foundation for most subsequent models. Robertson's model (which basically modified Webster's model to deal with high degrees of saturation) was used in the TRANSYT program. The 1985 HCM model [19] provides a recent addition to this field. Because the models have been broadly reviewed and compared from various aspects [2, 17, 24, 25], they will not be repeated here.

Actuated Signal Evaluation

Delays and stops for pretimed signals have been successfully analyzed, mainly because the operation of pretimed signals is simple. For semi-actuated signals, the dynamic characteristics of signal operation do not lend themselves well to analytical treatment. Simulation has been the most popular approach to assess delays and stops for actuated signals [4, 31, 44].

The limited analysis models for semi-actuated signals (or more broadly, for actuated signals) can be categorized into two approaches: direct analysis and indirect approximation. In the direct approach, the operational characteristics of an actuated phase are analyzed, and delays and stops are derived from the analysis. In indirect approximation, a substitute model (often borrowed from pretimed signals) is used to approximate delays and stops for semi-actuated signals.

In the direct analysis approach, Newell [36] developed a mathematical model for evaluating delays at actuated signals. The model is complicated even in the case of one-way streets. Following the work, Newell and Osuna [37] applied the model to two-way streets with symmetric traffic flows under the control of a two-phase signal. A purely theoretical model was studied by Lehoczky [30], which relies on input data that is difficult to obtain. Hoshi [22] developed an even more complicated model for a three-way intersection.

Papapanou [39] modified Robertson's pretimed model to assess the saturation delay under actuated control. Papapanou's model was incorporated into the Signal Operations Analysis Package (SOAP) [52]. Because saturation delay is significant only when traffic volumes are moderate to high but is negligible when traffic is light, Papapanou's model is not applicable in handling low volume conditions with phase skipping.

Lin [32] developed an algorithm to estimate average green times for full-actuated signals. The algorithm estimates the steady state green time of each actuated phase with an implicit assumption that the phase appears in every cycle. The assumption holds true when traffic volumes are moderate to high. In this situation, the actuated phase appears in almost every cycle, with phase length varying from cycle to cycle. However, the phase assumption is not valid under low volume conditions, since phase skipping occurs frequently due to lack of traffic demand.

Cowan [11] investigated average delays and average lengths of red and green phases for a two-street intersection operating with a full-actuated signal. However, his results cannot be applied to semi-

actuated signals, because semi-actuated signals are not a special case of full-actuated signals.

In conclusion, the existing analysis models for actuated signals either have limited applications, or rely on information that is difficult to obtain, or are restricted to moderate to high volumes. None of them are applicable to general operation of semi-actuated signals under low volume conditions.

The second approach of indirect approximation is more common and easier to apply. In the 1985 HCM [19], delay is first computed without distinguishing among signal control types, then is multiplied by different factors, according to signal control and traffic arrival type. (For example, in random arrival condition, the factors are 0.85 for actuated signals and 1.0 for semi-actuated signals.) In the delay calculations, average values (such as average cycle length and green times) of actuated signals are used in the delay equation originally developed for pretimed signals.

To assess stop probability for actuated signals in SOAP [52], average cycle length and green times of actuated signals are entered into the stop probability equation originally developed by Webster and Cobbe [57] for pretimed signals. TRANSYT Enhanced Version for Actuated Signals (TRANSYT-7FC) [5], although it does a better job in estimating timing for actuated signals, adopts this same method to assess delays and stops for actuated signals.

The underlying assumption of the indirect approximation approach is that the actuated phase appears in every cycle. As stated above, the assumption is tenable only when traffic volumes are moderate to high, and is false under low volume conditions. Therefore, this approach is

not directly applicable when traffic is light, unless phase skipping and dwelling are taken into account.

So far, the signal evaluation has been based on the implicit assumption that signals are isolated, so that vehicle arrivals are more or less random. When signals are coordinated, however, the random arrival assumption is generally not valid, since the arriving vehicles are the output stream from the upstream intersection. In this case, arriving vehicles are usually grouped into platoons by the upstream signal. The delay and stops at the intersection will be significantly affected by progression in terms of the relationship between the signal green time and the platoon arrival. The approaches to account for progression have evolved broadly in two directions: system approach and individual intersection approach. In the system approach, more than one intersection (at least the two adjacent intersections) are handled simultaneously, and in the individual intersection approach, each intersection is treated separately.

System Approach for Progression

TRANSYT [45] provides an excellent example of the system approach. TRANSYT simulates macroscopic traffic flows in the form of platoon dispersion from the upstream intersection to the downstream one. In doing so, the signal timing and traffic flows of the adjacent intersections are considered simultaneously.

A flow profile which combines the vehicle arrival and departure curves at each intersection is estimated in TRANSYT for the purpose of estimating delay and stops. Delay is then calculated by integrating the area under the curve in the red and saturation green times and by applying Robertson's random delay equation. The number of vehicles

stopped is basically equal to the number of vehicles arriving while a queue is present.

TRANSYT calculates delays and stops from predicted flow profiles. The Split, Cycle, and Offset Optimization Technique (SCOOT) [23], which was developed by the Transport and Road Research Laboratory in Great Britain, measures the upstream flow profiles by using detectors on the streets, then projects them downstream using the same model in TRANSYT. In any event, delays and stops are from detailed analysis of traffic flow profiles in the two systems.

As pointed out by Hurdle [24], the detailed analysis of flow profiles is a good approach to account for progression, but just as obviously it is not always a practical one. It is a computer simulation oriented approach, so that it is generally not practical for hand calculation. Its advantages are likely to be realized only when good data are available, and the approach is highly dependent upon signal timing. The approach is most useful for a large system, rather than for the usual situations in which only a few intersections are to be studied.

Individual Intersection Approach for Progression

The individual intersection approach provides an easier way to assess the effect of signal progression, especially for hand calculation.

Staniewicz and Levinson [53] used graphic analysis on time-space diagrams to develop delay equations for two extreme conditions, namely the first vehicle in the platoon arrives during a green interval, and the first vehicle in the platoon arrives during a red interval. Accompanied with the simplified assumptions, such as all vehicles

traveling in the platoon with no platoon dispersion, the study provided an analytical tool to estimate delay for special cases.

A more complicated analysis to estimate delay under progression was proposed by Rouphail [50]. The study considered platoon dispersion by assuming that traffic flow occurs in two distinct flows, one inside the progression band and another outside the band. With this assumption and a regression model of platoon dispersion, which is a function of travel time, Rouphail provided a method to estimate delay using information available from a time-space diagram.

The 1985 HCM [19] offers an easier way to account for progression. In the HCM, a progression adjustment factor (PF) is used to assess the influence of traffic progression, rather than using complicated equations. Delay for each intersection is originally computed with no consideration of progression, then a final progression adjustment is performed. The values of PF vary primarily based on arrival type and degree of saturation. In this approach, the classification of arrival types is very important, since it attempts to describe the nature of the progression. The dominant arrival flows are classified into five types. Higher type indicates better progression.

There are two major concerns associated with the HCM method: (1) arrival type is difficult to assess subjectively, and (2) progression adjustment factors may not reflect the actual influence of progression quality. To cope with the difficulty in subjectively assessing arrival type, the HCM suggests the use of platoon ratio to quantify the arrival type. The platoon ratio is defined as

$$R_p = \frac{PVG}{PTG} \tag{2.1}$$

where R_p = platoon ratio;

PVG = percentage of all vehicles in the movement arriving during the green phase; and

PTG = percentage of the cycle that is green for the movement.

PTG can be easily computed from the green and cycle times, but field observations are needed to determine PVG. The relationship between platoon ratio and arrival type is provided in Table 9-2 of the HCM.

To overcome the drawback that platoon ratio must be determined from field observations, Courage et al. [10] developed an estimator of the platoon ratio, which is called band ratio. The band ratio is defined as

$$R_b = \frac{C}{G_d}\left[\frac{B\,P_a}{G_o} + \frac{(G_d - B)(1 - P_a)}{C - G_o}\right] \tag{2.2}$$

where R_b = band ratio;

C = cycle length;

B = band width;

G_o = the green time at the upstream signal;

G_d = the green time at the downstream signal;

P_a = the proportion of traffic entering the upstream intersection from the artery; and

$1 - P_a$ = the proportion of traffic entering the upstream intersection from the cross street.

The band ratio can be derived from traffic volumes and time-space diagrams without field studies. The test of the band ratio indicated

that the field measurement of platoon ratio provides more reliable indicator of progression quality, but the band ratio offers acceptable substitute when field data are not available.

With regard to the second concern, accuracy of adjustment factors, Prevedouros and Jovanis [42] reported from a limited validation at actuated signals in Illinois that PF values collected from the field are lower than those provided in Table 9-13 of the HCM. A paper by Courage et al. [10] compared the PF values in the HCM with those generated from TRANSYT-7F [56], and concluded that there was good agreement between the two models, but that a wider range of PF values exists than the HCM recognizes. The study suggested that some extrapolation of the HCM PF values may be warranted to cover exceptionally good and exceptionally poor progression. Another paper by Courage and Luh [8] attempted to compute service volumes at signalized intersections, and reported that due to the threshold PF values in the HCM, the effect of progression on delay is discontinuous.

Recognizing these problems, the Texas Transportation Institute initiated a comprehensive study, which was completed recently [6]. The study examined the PF values in the HCM using extensive simulation and delay data collected nationwide. The results of this study have not yet been published.

From the above literature review, it can be concluded that the 1985 HCM provides a practical method for evaluating signal performance under traffic progression. When applying the method, arrival type can be assessed either by field observations (if applicable) or by computing band ratio from time-space diagrams.

Decision Between Coordination and Free Operations

A number of techniques have been found in the literature which are relevant to making the decision between coordination and free operations.

Yagoda et al. [59] developed the coupling index, a simple ratio of link volume and link length, to determine which signals to coordinate. In its application, the coupling index for each link is computed. A coupling threshold is defined so that all links with coupling indices below the threshold are assumed not to require coordination. By adjusting the coupling threshold, the network (a group of intersections) can be broken into several parts. The boundaries among these parts are thereby identified as suitable candidates for subdivision of coordination. An analysis of benefits is finally conducted by using a signal optimization program to establish the validity of the coordination divisions. This method provides a simple and straightforward technique to determine which signals to coordinate.

Based on this idea, a more complicated interconnection desirability index was developed by Chang [7]. The index attempts to determine the need to coordinate a pair of adjacent signals. The index considers many factors, such as intersection spacing, traffic traveling speed, traffic volumes, and number of lanes. The index has a range of values from zero to one. When the index has a value of 0.25 or less, isolated operation is recommended. Conversely, when the index has a value of 0.50 or greater, interconnection of the two adjacent signals is recommended. Other evaluation methods are needed to assist in the interconnection decision if the calculated value of the index is between 0.25 and 0.50 [7]. Since the index considers only adjacent pairs of signals at any

one time, a piece-wise coordination might result from this method. Furthermore, though deemed necessary by the author when the index has a value between 0.25 and 0.50, the supplementary evaluation indicators were not provided.

Another technique for deciding about coordination is found in the Second Generation (2-GC) of Urban Traffic Control Systems [13, 20]. The 2-GC of UTCS contains an on-line optimization routine which determines the control parameters that will minimize the total delay and stops within the system in response to current traffic conditions. A sub-network configuration model called RTSND [13] resides in this system to determine whether to break the coordination among signals. The determination is primarily based upon cycle lengths. The coordination of signals is maintained if they have similar cycle lengths; otherwise, the interconnection is released.

Another similar method was used in the Sydney Coordinated Adaptive Traffic System (SCATS) [33], which was developed by the Department of Main Roads, New South Wales in Australia. In SCATS, a coordination criterion and a coordination vote computational algorithm were developed to on-line determine whether to coordinate signals or not. A coordination vote is calculated every cycle. The vote is in favor of coordination if the difference of cycle lengths is less than 9 seconds. A counter is increased by one if a vote is in favor of coordination, but is otherwise decreased by one. The signals are coordinated when the counter attains a value of four, but the interconnection is broken when the counter reaches zero.

The techniques used in the above two systems (2-GC of UTCS and SCATS) use similar cycle lengths as the sole criterion in the

determination of whether or not to coordinate. The reason is primarily based on the fact that most signal coordination operations require a common cycle length. In other words, the techniques do not consider any potential benefits in making the decision.

Exploration of Personal-Computer-Based Signal Systems

A variety of traffic-responsive, computer-controlled systems has evolved over the past two decades. Most of the systems presently operating in the United States have been centered around Urban Traffic Control Systems (UTCS), which were established by the Federal Highway Administration in the early 1970s. Personal-computer-based (PC-Based) signal control systems are a new tool to supervise area-wide traffic signals. The number of PC-Based signal systems in this nation has grown significantly since the mid-1980's. Since this type of signal control is newer, its capabilities are explored in this study.

Because the traffic engineering community is familiar with UTCS, it would serve a good basis for understanding PC-Based systems. In the following, UTC systems and their major disadvantages are first briefly reviewed. PC-Based systems are then described by way of their contrasts with UTCS. Last is the discussion of the PC-Based systems' capabilities.

Although there exist some variations among UTC systems, the basic configuration in predominant use in UTCS is illustrated in Figure 2.1 [41, 54]. The dominant characteristic of UTCS is the location of all decision making capability at one geographic point and on one level. Data from all detectors in the system are fed into the central computer, where all decisions and control commands are made and dispatched to local controllers.

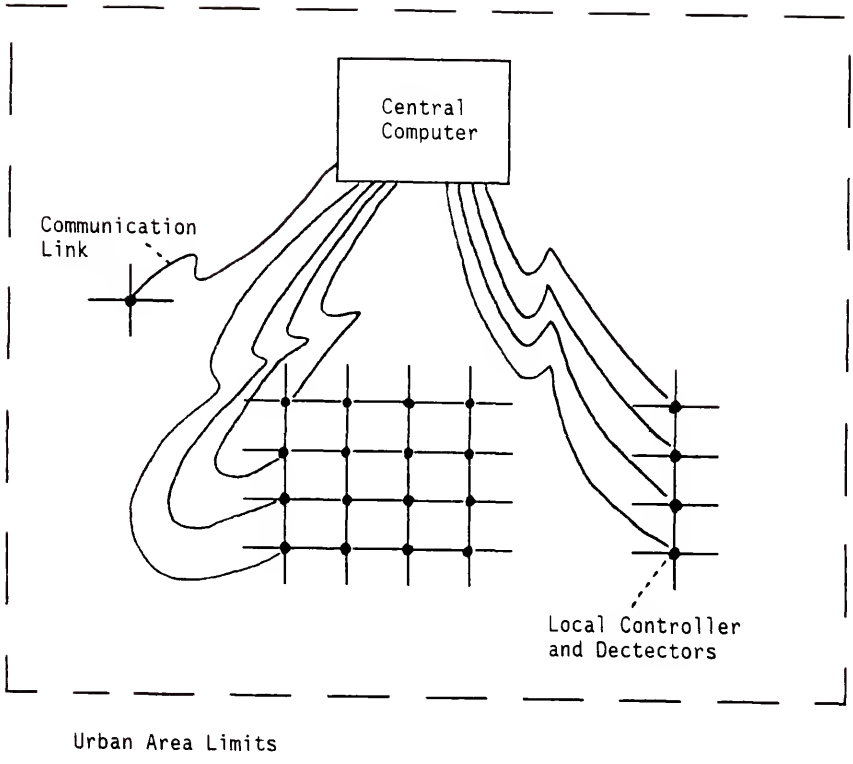


Figure 2.1. Basic Configuration of Urban Traffic Control Systems.

The heavy workload on the central computer and the direct communication between the central computer and local controllers require most UTC systems to depend on large computers and complex dedicated communication systems. Because of this, several disadvantages have been experienced in the design and maintenance of such large centralized control systems. UTC systems are costly. Since the exclusive use of user-owned twisted pair cable has been accepted as standard for traffic control communication in UTCS for many years [54], the communication may constitute as much as 50 to 60% of the total project cost [28]. Hence, a project cost could be tremendously high when control is desired over a great number of signals, spread over a large geographic area.

User involvement is another concern associated with UTCS in many communities. Staff in small to medium communities generally lacks expertise in the area of traffic control systems. The capabilities of staff in small jurisdictions are limited. The limited personal resource cannot be allocated to a continuous commitment for operating a complex control system [27]. Also, a complex system requires longer set-up time. These disadvantages have prevented many jurisdictions from taking advantage of traffic-responsive, computer-controlled systems [9].

In contrast to UTC systems, PC-Based traffic signal systems offer a cost effective alternative for traffic-responsive computer-control. The basic configuration of PC-Based systems is illustrated in Figure 2.2. A central personal-computer is interconnected with several on-street masters or a number of local controllers. Typically, telephone lines are used between the central personal-computer and on-street masters. Each on-street master is simultaneously connected to a number of local

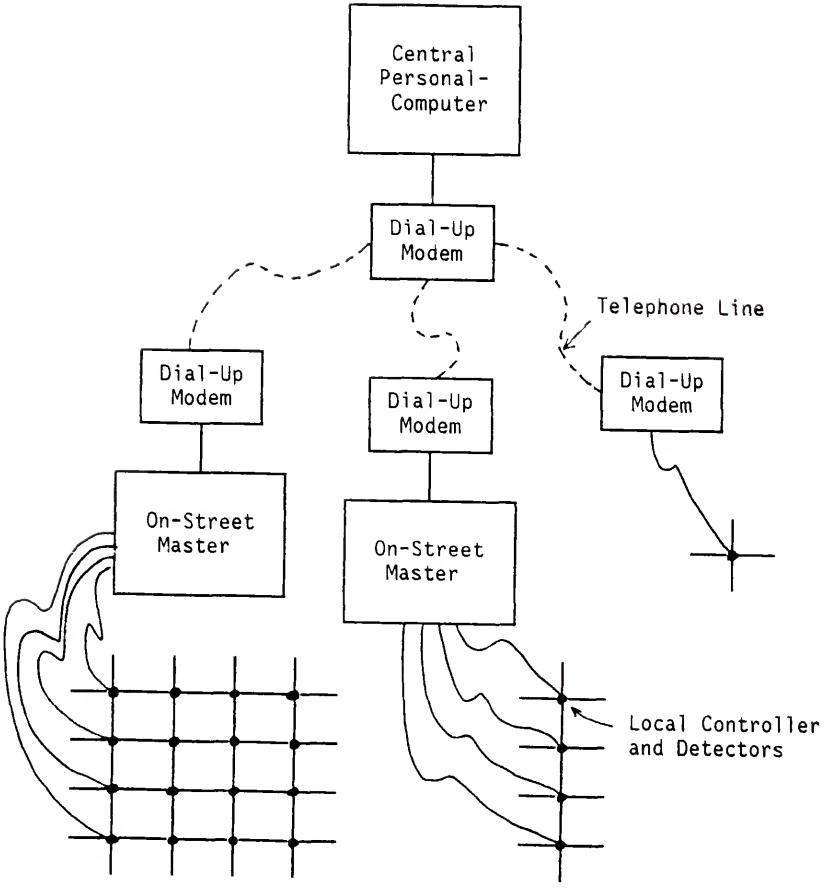


Figure 2.2. Basic Configuration of PC-Based Traffic Signal Control Systems.

controllers with more sophisticated, higher-capacity media, such as twisted pair cable.

There are many features which separate personal-computer-based systems from UTC systems. The major ones involve the role of the central personal-computer and the communication system. The central personal-computer is not a master-control, system-host machine. It functions as a system data logger and as a central editing and reporting station for overall monitoring. Close monitoring and interface with the on-street masters is not necessary, and the central personal-computer can be turned off or used for other activities. The tasks of selecting signal plans in response to traffic demand and supervising local controllers are distributed to on-street masters. The on-street masters function on a stand-alone basis, and primarily operate in traffic-responsive mode, based on surveillance data gathered from sub-system detectors.

The communication system, as illustrated in Figure 2.2, groups local signals into sub-systems. A sub-system may consist of a single intersection but normally contains one section of an arterial, a small grid network, or any other signal group requiring coordination. Sub-systems are generally independent unless coordination is provided from the central site. This structure of building blocks permits future expansion (additional sub-systems) without major modification to existing hardware.

PC-Based signal systems generally provide three operational modes: manual, time of day and day of week (TOD/DOW), and traffic responsive (TRSP). The three modes represent three degrees in response to traffic demand. The manual mode is often used for handling unusual traffic

conditions, such as traffic congestion resulting from football game or concert. The TOD/DOW mode changes the timing plans according to a preset schedule. The TRSP mode selects the plan from the timing plan library that is best suited to the current traffic conditions. The match is based on the combination of volume and occupancy data gathered from system detectors. (The Gainesville, Florida, Signal System currently operates on the TOD/DOW mode.)

The timing plans used in both the TOD/DOW and TRSP modes are developed off-line, using programs such as TRANSYT. A day is broken into several time periods to represent the various traffic characteristics, and the average parameters (such as volumes) in each period are used in the timing development.

CHAPTER THREE
ANALYTICAL METHOD FOR PERFORMANCE EVALUATION OF SEMI-ACTUATED SIGNALS AT LOW VOLUMES

Introduction

This chapter presents a method to directly estimate stop probabilities and average delays for semi-actuated signals at low volumes, under both isolated and coordinated controls. The method uses probability theory and stochastic processes to consider the various cycle patterns in terms of red and green times. Also, stop probability and average delay of each cycle pattern are estimated using equations developed in this chapter. The method will be referred to as the Analytical Method.

This chapter first addresses the assumptions in modeling delays and stops. Then the Analytical Method is explained, and applied to both control types. Next the mathematical model in this method is validated against simulation. After the validation, results obtained from the Analytical Method are compared with those from a model for pretimed signals. The summary and discussions follow. Finally, the stop probability and average delay equations used in the Analytical Method are developed.

Assumptions and Notations

This section first addresses the assumptions in modeling delays and stops. The signal operations under consideration then follow. The notations used throughout the dissertation are listed finally.

Arrival and Departure Times

As in many delay models, vehicles are regarded as identical in size and performance. They are assumed to arrive and depart the intersection at a constant speed, and delay is regarded as time spent at the stop line. In other words, stopped delays are of concern, and deceleration and acceleration are not considered. The queue is regarded as a vertical stack at the stop line. Vehicles are assumed to pass the stop line at a constant rate so long as there are vehicles waiting at the stop line. After the waiting queue has fully discharged, vehicles arriving in the remaining green time are assumed to pass the stop line without any delay. Yellow and lost times are not considered.

Vehicle Arrivals

Moreover, vehicles of the actuated phases are assumed to have Poisson arrivals [2, 16], which means that the probability of n arrivals in a time interval has a Poisson distribution [16]. (Please note that it is unnecessary to assume Poisson arrivals for the non-actuated phase in this study since the non-actuated phase is not controlled by vehicle detections.)

Steady State

It is assumed that the system has operated for a sufficiently long time with the same average traffic volume and vehicle departure rate to have settled into a steady state [24].

Signal Operations

The method presented in the dissertation is based on a typical semi-actuated signal with the following characteristics [54]:

1. Detectors are located only on actuated-phase approaches.
2. Detectors are placed near the stop line (presence detectors).

3. The non-actuated phase receives at least the minimum green interval each cycle.
4. The actuated phases receive green upon actuation, provided that the non-actuated phase has completed its minimum green interval.
5. A signal under coordinated control has a background cycle length, but a signal under isolated control does not.
6. The following are preset: the background cycle length for coordinated control, the minimum green time for the non-actuated phase, and initial green intervals for actuated phases.

For simplicity, it is assumed that there is only one non-actuated phase, and all others are actuated. Actuated phases are assumed to terminate their green times after the initial green intervals elapse, since the probability of requiring green extensions after the completion of the initial green interval is usually very small under low volumes. The probability of an actuated phase having arrivals more than the departure capacity of the initial green interval (i.e., requires green extensions) can be estimated by the following equation:

$$\text{probability} = I - \sum_{n=0}^{\text{capacity}} \frac{u^n e^{-u}}{n!} \qquad (3.1)$$

where u = (red time + green time) * volume / 3600

capacity = (green time)/(saturation headway)

saturation headway = 2 seconds

It can be easily verified that in most cases the probabilities are very small where volumes are less than 300 vehicles per hour per lane (vphpl). Because of this, 300 vphpl is taken as the upper bound for this method.

Since the actuated phases of a semi-actuated signal may be skipped, it is not clear at the first glance in determining a cycle. Under isolated control, two successive occurrences of the non-actuated phase will be referred to as a cycle. As will be explained later, a cycle consists of the non-actuated phase plus at least one actuated phase. Under coordinated control, a background cycle will be referred to as a cycle. In this case, a cycle generally consists of the non-actuated phase plus actuated phases, but may solely consist of the non-actuated phase.

Traffic Progression

Stop probabilities and average delays at individual intersections are influenced by the quality of traffic progression from their neighbors. When the signal progression is favorable to the subject traffic movement, stop probabilities and average delays will be considerably less than those for random arrivals. Conversely, when signal progression is unfavorable, stop probabilities and average delays can be considerably higher than those for random arrivals [19]. When signals are under isolated control, no progression is considered. When signals are under coordinated control, the non-actuated phase (which controls the major street traffic) is considered under the influence of progression, but actuated phases (which control the minor street traffic) are not.

Notations

The following notations are used throughout the dissertation. Where applicable, a subscript i indicates the i^{th} phase.

C = cycle length in seconds;

C_B = background cycle length in seconds of a coordinated signal;

d = average delay in seconds per vehicle;

D = total delay in seconds in a cycle;

d_{int} = average delay in seconds per vehicle for an intersection as a whole;

$f(t)$ = probability density function that the headway of traffic is t;

$F(t)$ = probability that the headway of traffic is less than t;

g = green time in seconds;

G = average green time in seconds;

G_{dwl} = expected dwell time in seconds of the non-actuated phase;

G_{min} = minimum green interval in seconds of the non-actuated phase;

g_s = saturation green time in seconds;

G_s = average saturation green time in seconds;

G_{sla} = slack time in seconds of the non-actuated phase;

N = number of vehicles in a cycle;

Nc = number of cycles;

Nd = number of green occurrences with a zero effective red time;

Ng = number of green occurrences;

Nr = number of green occurrences with a positive effective red time;

Ns = number of phase skip occurrences;

N_{stop} = number of vehicles stopped in a cycle;

P = transition function, which is a square matrix of $P(i,j)$;

$P(i)$ = stationary probability that cycle 1 is in state (i);

$P(i,j)$ = transition probability from state (i) to state (j);

$P_k(i,j)$ = sub-transition probability of sub-transition k from state (i) to state (j);

Ps = stop probability;

Ps_{int} = stop probability for an intersection as a whole;

r = red time in seconds;

R = average red time in seconds;

r(n,t) = probability of having n arrivals in a time interval t;

s = saturation flow rate in vehicles per second;

v = volume in vehicles per second;

x = volume to capacity ratio;

π = stationary distribution, which is a horizontal vector in the form of (P(1),P(2),...,P(n)); and

π^t = transposed vector of π ;

Method Development

An actuated phase will be either skipped or present in a cycle. If the phase is skipped, it has no traffic demand up to the yield point, which is defined as the moment when the controller is ready to serve the phase. If the phase is present, all its traffic demand is assumed to be serviced in the green time (as previously stated). Therefore, the presence of the actuated phase in the next cycle depends simply on whether, if skipped in the current cycle, it receives actuations after the yield point, or, if present in the current cycle, it receives actuations after the end of the green time. In other words, two consecutive cycles are involved in determining the presence of an actuated phase. Because of this property, the operation of a semi-actuated signal can be described by two consecutive cycles, and the system can be treated as a Markov chain [21]. For notation convenience, the previous cycle is denoted as cycle 1 and the current cycle as cycle 2. A phase sequence in a cycle will be treated as a "state" in terms of Markov chains, and two consecutive cycles will constitute a

"transition", again, in Markov terms. It is clear that there are total of n*n transitions if there are n states in one cycle.

Method Description

The method is conducted on a phase by phase basis for individual intersections. There are two basic inputs: traffic volumes and signal settings, such as the background cycle length and the minimum green intervals. The complete analysis procedure is illustrated in Figure 3.1, which shows the five computational steps: determine transitions, compute transition and stationary probabilities, determine patterns, compute pattern probabilities, and compute stop probabilities and average delays. The first four steps are to consider the various cycle patterns and their probabilities. A cycle pattern is defined as a specific combination of a red time and a green time. The last step is to estimate stop probability and average delay for each cycle pattern and for the intersection as a whole.

In Step 1, transitions are determined from all the combinations of possible states in two consecutive cycles. Step 2 computes transition and stationary probabilities. Transition probability, which is a conditional probability of cycle 2 being in one state given that cycle 1 is in a known state [21], is determined from the Poisson distribution in the following way. Assuming that the volume of an actuated phase is v, the probability that this phase is not activated during a time interval of r is e^{-vr}, while the probability of it being activated in r is $1 - e^{-vr}$.

Since the system is a Markov chain, stationary probability, which is the probability that cycle 1 is in a given state, is computed from the following equation [21]:

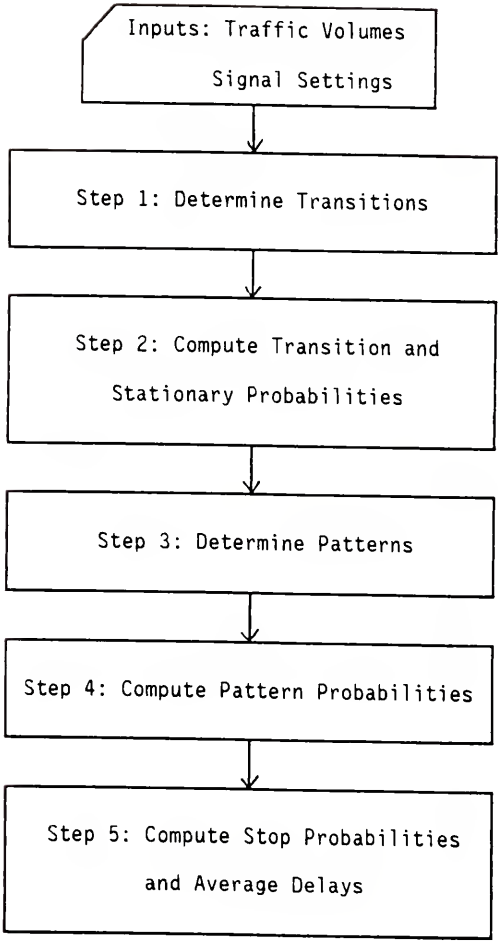


Figure 3.1. Block Diagram of the Analytical Method.

$$\pi * P = \pi^{t} \tag{3.2}$$

Step 3 is to identify all the possible cycle patterns in terms of red and green times. Red and green times can be directly measured on transitions. Identical red and green times may appear in differing transitions. For the non-actuated phase, both the red and green times may vary from pattern to pattern. For actuated phases, only red times may vary since the phases are assumed to terminate the green times after the initial green intervals complete.

In Step 4, pattern probability is then computed from summing up the product of stationary and transition probabilities of the transitions that produce the pattern.

Finally in Step 5, stop probability and average delay for each cycle pattern are computed using the following equations which are developed in the last section of this chapter.

$$Ps = \frac{r + g_s}{r + g} \tag{3.3}$$

$$d = \frac{r}{2.6} Ps \tag{3.4}$$

$$Ps = e^{-vr} + (1 - e^{-vr}) \frac{r + g_s}{r + g} \tag{3.5}$$

$$d = \frac{r^2}{2(r + g)} + e^{-vr} \frac{g(g + 2r)}{2(r + g)} + (1 - e^{-vr}) \frac{g_s^2}{2(r + g)} \tag{3.6}$$

$$Ps = \frac{1}{vg + 1} \tag{3.7}$$

$$d = 0 \tag{3.8}$$

where $g_s = \frac{vr}{s - v}$ (3.9)

For clarity, the above equations and the conditions for their use are summarized in Figure 3.2. Equations (3.3) and (3.4) are for the patterns of the non-actuated phase. Equations (3.5) and (3.6) are for those of the actuated phases with positive effective red times. Otherwise, for actuated phases with a zero effective red time, Equations (3.7) and (3.8) should be used. The difference between a positive effective red time and a zero effective red time will be explained later in Step 3 of the section of Isolated Control.

Once the stop probability and average delay of each cycle pattern is computed, the next task is to compute the phase stop probability and average delay. The phase average delay is treated first.

The total vehicle arrivals (N) in one cycle of a pattern can be estimated by multiplying the average arrival rate and the sum of the red and green times of the pattern, i.e.,

$$N \text{ of pattern } j = v(r + g) \quad (3.10)$$

The total delay in one cycle of the pattern can also be estimated by multiplying the average delay and the total arrivals, i.e.,

$$D \text{ of pattern } j = v(r + g)d \quad (3.11)$$

The expected arrivals across the patterns is the sum of the products, for all patterns, of the total arrivals of each pattern multiplied by the corresponding pattern probability, i.e.,

$$N \text{ of phase } i = \sum_{\text{all } j} [(N \text{ of pattern } j) * (\text{probability of pattern } j)] \quad (3.12)$$

The expected delay across the patterns is the sum of the products, for

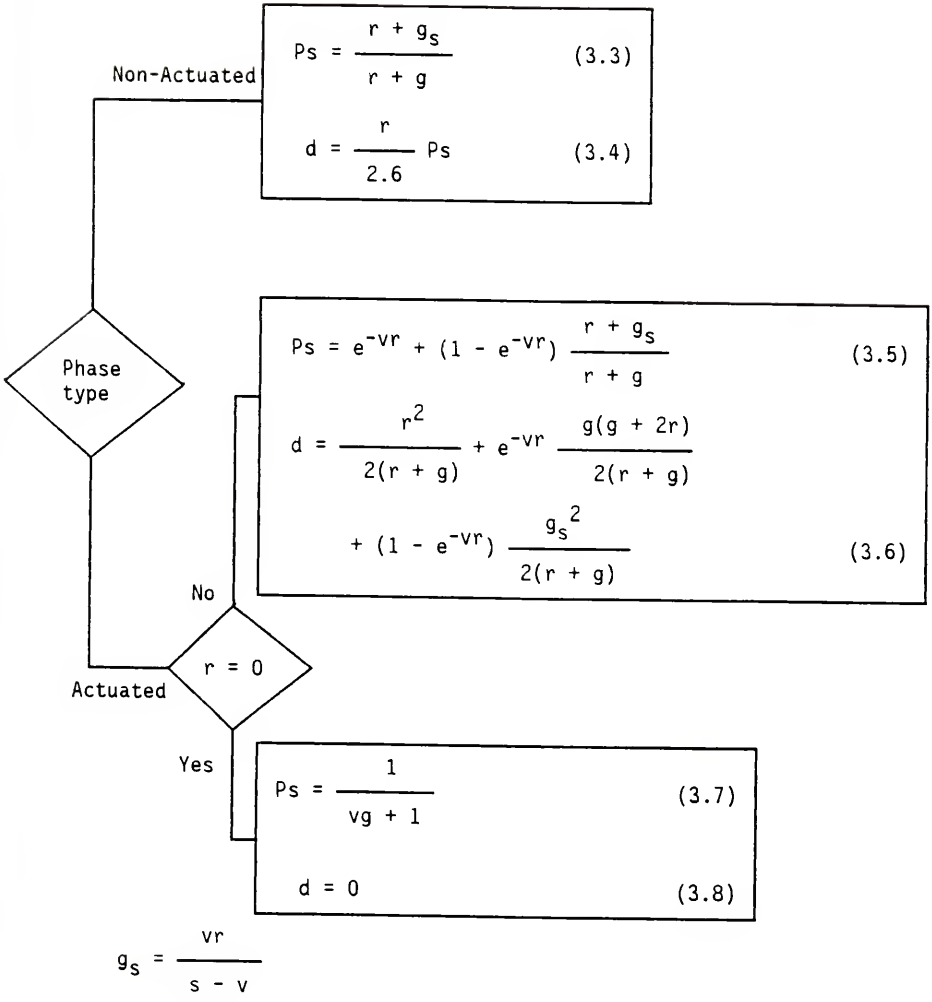


Figure 3.2. Stop Probability and Average Delay Equations and the Conditions for Their Use Under the Analytical Method.

all patterns, of the total delay of each pattern multiplied by the corresponding pattern probability, i.e.,

$$\text{D of phase } i = \sum_{\text{all } j} [(\text{D of pattern } j) * (\text{probability of pattern } j)] \quad (3.13)$$

Combining (3.12) and (3.13), the average delay for phase i is the expected delay divided by the expected arrivals, i.e.,

$$d_i = \frac{\text{D of phase } i}{\text{N of phase } i} = \frac{\sum_{\text{all } j} [(\text{D of pattern } j) * (\text{probability of pattern } j)]}{\sum_{\text{all } j} [(\text{N of pattern } j) * (\text{probability of pattern } j)]} \quad (3.14)$$

The average delay for the intersection as a whole, therefore, is

$$d_{int} = \frac{\sum_{i=1}^{\#\text{ of phases}} (d_i v_i)}{\sum_{i=1}^{\#\text{ of phases}} v_i} \quad (3.15)$$

The computations of stop probability follow the same logic. The number of vehicles stopped (N_{stop}) in one cycle of a pattern can be estimated by multiplying the stop probability and the total arrivals, i.e.,

$$N_{stop} \text{ of pattern } j = v(r + g)Ps \quad (3.16)$$

The expected N_{stop} across the patterns is the sum of the products, for all patterns, of the N_{stop} of each pattern multiplied by the corresponding pattern probability, i.e.,

$$N_{stop} \text{ of phase } i = \sum_{\text{all } j} [(N_{stop} \text{ of pattern } j) * (\text{probability of pattern } j)] \quad (3.17)$$

Combining (3.12) and (3.17), the stop probability for phase i is the expected N_{stop} divided by the expected arrivals, i.e.,

$$Ps_i = \frac{N_{stop} \text{ of phase } i}{N \text{ of phase } i}$$

$$= \frac{\sum_{\text{all } j} [(N_{stop} \text{ of pattern } j) * (\text{probability of pattern } j)]}{\sum_{\text{all } j} [(N \text{ of pattern } j) * (\text{probability of pattern } j)]} \qquad (3.18)$$

The stop probability for the intersection as a whole is

$$Ps_{int} = \frac{\sum_{i=1}^{\#\text{ of phases}} (Ps_i v_i)}{\sum_{i=1}^{\#\text{ of phases}} v_i} \qquad (3.19)$$

The applications of the method to both isolated and coordinated controls are presented below.

Isolated Control

A three-phase signal under isolated control is illustrated, but the logic can be systematically expanded to signals with more than three phases.

Step 1: Determine Transitions. There are three possible states in any one cycle, based on whether phase 2 or 3 is skipped or not. The three states are (1) phase 1, then phase 2, and finally phase 3; (2) phase 1 followed by phase 2 only; and (3) phase 1 followed by phase 3 only. State 1 is the normal phase sequence, in which no actuated phase is skipped. State 2 means that phase 2 is followed by phase 1 of the next cycle. Namely, phase 3 is skipped. This state occurs when phase 3 is not activated before the end of phase 2. Similarly, phase 2 is skipped

in state 3. This state occurs when phase 2 is not activated before the end of phase 1, but phase 3 is. The nine transitions constituted by the three states are shown in Figure 3.3.

It can be seen in this figure, each transition is further split into two sub-transitions based on phase 1's green length in cycle 2. In sub-transition 1, phase 1's green time (g_1) in cycle 2 is the minimum green time (G_{min}). In sub-transition 2, g_1 is greater than G_{min}. Sub-transition 1 occurs when at least one of phases 2 and 3 is activated before the end of G_{min}. In this case, the green light will switch from phase 1 to the activated phase(s) after the completion of G_{min}. Sub-transition 2 occurs when both phases 2 and 3 are not activated before the end of G_{min}. In this case, the green light will dwell on phase 1 until any one of them is activated. Therefore, phase 1's green time in sub-transition 2 is always longer than that in sub-transition 1. The green time of phase 1 extended beyond G_{min} is called dwell time. The length of dwell time can be estimated in the follow way:

Let $f_2(t)$ be the probability density function that the headway of phase 2 is t, and $F_3(t)$ be the probability that the headway of phase 3 is less than t, the expected dwell time of the case that phase 2 terminates the dwell is

$$
\begin{aligned}
G_{dwl2} &= \int_0^\infty t\, f_2(t)\, [1 - F_3(t)]\, dt \\
&= \int_0^\infty t\, v_2 \exp(-v_2 t) \exp(-v_3 t)\, dt \\
&= v_2 \int_0^\infty t \exp[-(v_2 + v_3)t]\, dt \\
&= \frac{v_2}{(v_2 + v_3)^2}
\end{aligned}
\tag{3.20}
$$

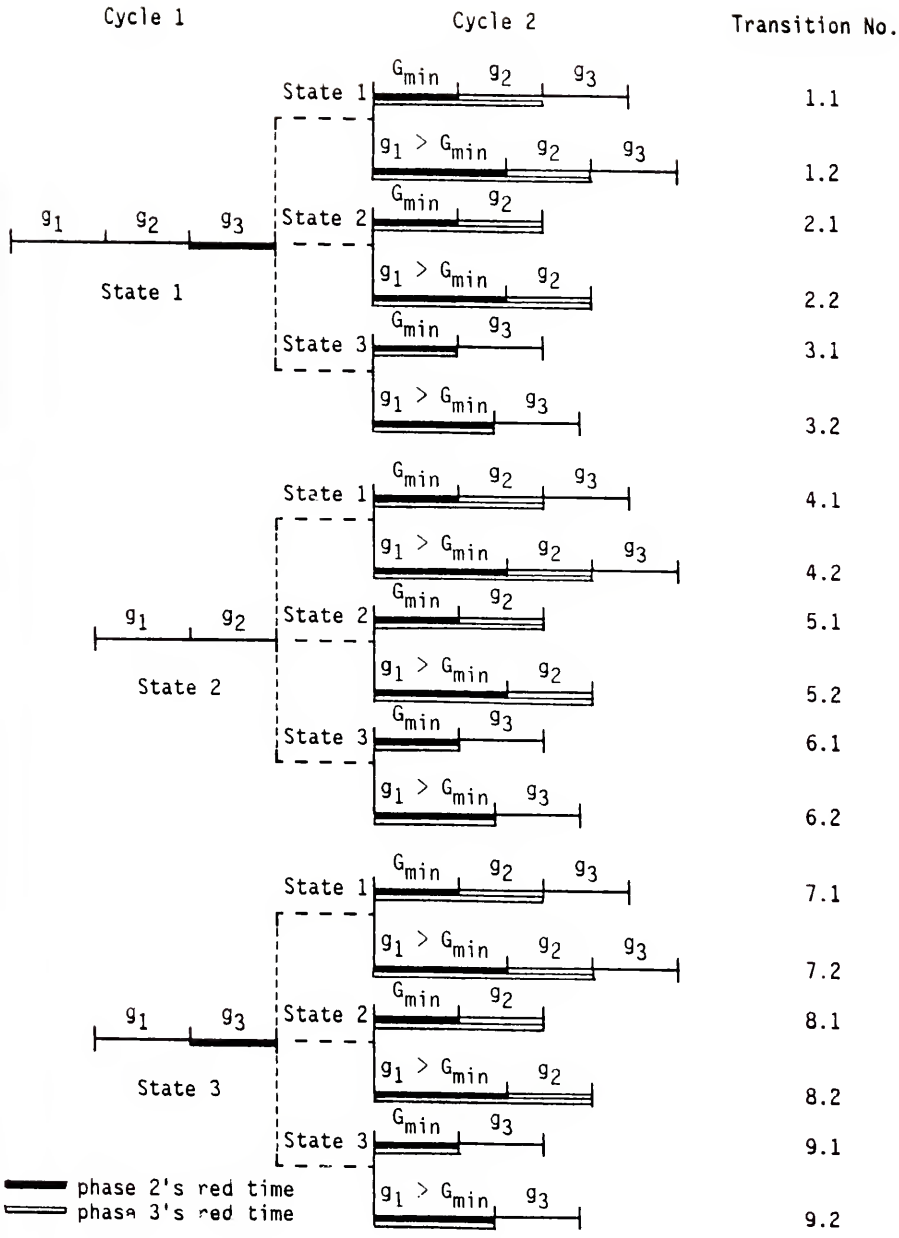


Figure 3.3. Transitions, Red Times, and Transition Probabilities at a Three-Phase Semi-Actuated Signal Under Isolated Control.

Transition No.	Transition probability
1.1	$P_1(1,1)=\{1-\exp[-v_2(g_3+G_{min})]\}\{1-\exp[-v_3(G_{min}+g_2)]\}$
1.2	$P_2(1,1)=\exp[-v_2(g_3+G_{min})]\exp(-v_3G_{min})v_2/(v_2+v_3)[1-\exp(-v_3g_2)]$
2.1	$P_1(1,2)=\{1-\exp[-v_2(g_3+G_{min})]\}\exp[-v_3(G_{min}+g_2)]$
2.2	$P_2(1,2)=\exp[-v_2(g_3+G_{min})]\exp(-v_3G_{min})v_2/(v_2+v_3)\exp(-v_3g_2)$
3.1	$P_1(1,3)=\exp[-v_2(g_3+G_{min})][1-\exp(-v_3G_{min})]$
3.2	$P_2(1,3)=\exp(-v_2G_{min})\exp(-v_3G_{min})v_3/(v_2+v_3)$
4.1	$P_1(2,1)=[1-\exp(-v_2G_{min})]\{1-\exp[-v_3(G_{min}+g_2)]\}$
4.2	$P_2(2,1)=\exp(-v_2G_{min})\exp(-v_3G_{min})v_2/(v_2+v_3)[1-\exp(-v_3g_2)]$
5.1	$P_1(2,2)=[1-\exp(-v_2G_{min})]\exp[-v_3(G_{min}+g_2)]$
5.2	$P_2(2,2)=\exp(-v_2G_{min})\exp(-v_3G_{min})v_2/(v_2+v_3)\exp(-v_3g_2)$
6.1	$P_1(2,3)=\exp(-v_2G_{min})[1-\exp(-v_3G_{min})]$
6.2	$P_2(2,3)=\exp(-v_2G_{min})\exp(-v_3G_{min})v_3/(v_2+v_3)$
7.1	$P_1(3,1)=\{1-\exp[-v_2(g_3+G_{min})]\}\{1-\exp[-v_3(G_{min}+g_2)]\}$
7.2	$P_2(3,1)=\exp[-v_2(g_3+G_{min})]\exp(-v_3G_{min})v_2/(v_2+v_3)[1-\exp(-v_3g_2)]$
8.1	$P_1(3,2)=\{1-\exp[-v_2(g_3+G_{min})]\}\exp[-v_3(G_{min}+g_2)]$
8.2	$P_2(3,2)=\exp[-v_2(g_3+G_{min})]\exp(-v_3G_{min})v_2/(v_2+v_3)\exp(-v_3g_2)$
9.1	$P_1(3,3)=\exp[-v_2(g_3+G_{min})][1-\exp(-v_3G_{min})]$
9.2	$P_2(3,3)=\exp(-v_2G_{min})\exp(-v_3G_{min})v_3/(v_2+v_3)$

Figure 3.3. — continued.

Similarly, the expected dwell time of the case that phase 3 terminates the dwell is

$$G_{dwl3} = \frac{v_3}{(v_2 + v_3)^2} \tag{3.21}$$

Please note that it is unnecessary to split the parallel difference in cycle 1, since whether phase 1 dwells or not in cycle 1 will not affect the presence of the actuated phases in cycle 2.

Step 2: Compute Transition and Stationary Probabilities. The transition probabilities are also shown in Figure 3.3. Although they look complicated at the first glance, they can be easily established from basic Poisson distribution function. The following example illustrates how they are obtained.

Let $P_2(1,1)$ be the probability of sub-transition 2 from state 1 to state 1. It is shown in Figure 3.3 that in this sub-transition, phase 2's red time is g_3+G_{min}+(dwell time), and phase 3's is G_{min}+(dwell time)+g_2. This sub-transition occurs when the following conditions are satisfied: (1) both phases 2 and 3 are not activated before G_{min} expires; (2) phase 2 is first activated when the green light dwells on phase 1; and (3) phase 3 is activated during phase 2's green time. These conditions are formulated as follows:

$P_2(1,1)$

= P(phase 2 is not activated before G_{min} expires)

* P(Phase 3 is not activated before G_{min} expires)

* P(phase 2 is first activated when the green light dwells on phase 1)

* P(Phase 3 is activated when phase 2 is green)

$$= r(0,\ g_3+G_{min}) * r(0,\ G_{min}) * [v_2/(v_2+v_3)] * [1-r(0,\ g_2)]$$

$$= \exp[-v_2(g_3+G_{min})]*\exp(-v_3G_{min})*[v_2/(v_2+v_3)]*[1-\exp(-v_3g_2)] \qquad (3.22)$$

Once $P_k(i,j)$ is determined, k=sub-transition 1 or 2, the next task is to compute stationary probabilities. Let $P(i,j)=P_1(i,j)+P_2(i,j)$ for all i and j, and let P(i) be the stationary probability of state i, where i=1 to 3, P(i) can be obtained from solving the following equations:

$$[\ P(1),P(2),P(3)\ ] \begin{bmatrix} P(1,1) & P(1,2) & P(1,3) \\ P(2,1) & P(2,2) & P(2,3) \\ P(3,1) & P(3,2) & P(3,3) \end{bmatrix} = \begin{bmatrix} P(1) \\ P(2) \\ P(3) \end{bmatrix} \qquad (3.23)$$

with P(1)+P(2)+P(3)=1.

Step 3: Determine Patterns. All the possible patterns in terms of red and green times for the three phases are summarized in Table 3.1. For phase 1, the dwell time is included in the green time, since dwell extends the green time. For phases 2 and 3, the green times are fixed, but the determination of red times needs explanations.

When dwell occurs, the actuated phase following phase 1 terminates the dwell. In this case, the actuated phase has no arrival during the red time until it is activated by a vehicle (i.e., until the end of the dwell time). Similarly, when an actuated phase is skipped, there is no vehicle arrival during the corresponding red time. In order to distinguish from the actual red time, effective red time is used for the actuated phases, which subtracts the red time without arrivals from the actual red time. The effective red time is always positive in Sub-transition 1, but is zero for the actuated phase immediately following phase 1 in Sub-transition 2. In Table 3.1, Patterns 1 and 2 of

Table 3.1. Patterns (in Terms of Red and Green Times) and Their Probabilities at a Three-Phase Semi-Actuated Signal Under Isolated Control.

Phase	Pat.	Type of pattern	Pattern probability	Ps and d equations
1	1	$r=g_2+g_3$ $g=G_{min}$	$P(1)[P_1(1,1)+P_1(1,2)+P_1(1,3)]$	(3.3) (3.4)
	2	$r=g_2+g_3$ $g=G_{min}+G_{dwl2}$	$P(1)[P_2(1,1)+P_2(1,2)]$	
	3	$r=g_2+g_3$ $g=G_{min}+G_{dwl3}$	$P(1)P_2(1,3)$	
	4	$r=g_2$ $g=G_{min}$	$P(2)[P_1(2,1)+P_1(2,2)+P_1(2,3)]$	
	5	$r=g_2$ $g=G_{min}+G_{dwl2}$	$P(2)[P_2(2,1)+P_2(2,2)]$	
	6	$r=g_2$ $g=G_{min}+G_{dwl3}$	$P(2)P_2(2,3)$	
	7	$r=g_3$ $g=G_{min}$	$P(3)[P_1(3,1)+P_1(3,2)+P_1(3,3)]$	
	8	$r=g_3$ $g=G_{min}+G_{dwl2}$	$P(3)[P_2(3,1)+P_2(3,2)]$	
	9	$r=g_3$ $g=G_{min}+G_{dwl3}$	$P(3)P_2(3,3)$	

where $G_{dwl2} = \dfrac{v_2}{(v_2 + v_3)^2}$

$G_{dwl3} = \dfrac{v_3}{(v_2 + v_3)^2}$

r = red time
g = green time

Table 3.1. — continued.

Phase	Pat.	Type of pattern	Pattern probability	Ps and d equations
2	1	$r=G_{min}$ $g=g_2$	$P(2)[P_1(2,1)+P_1(2,2)]$	(3.5)
	2	$r=g_3+G_{min}$ $g=g_2$	$P(1)[P_1(1,1)+P_1(1,2)]+[P(1)P(1,3)+P(2)$ $P(2,3)+P(3)][P_1(3,1)+P_1(3,2)]/[1-P(3,3)]$	(3.6)
	3	$r=0$ $g=g_2$	$P(1)[P_2(1,1)+P_2(1,2)]+P(2)[P_2(2,1)$ $+P_2(2,2)]+P(1)P(1,3)+P(2)P(2,3)+P(3)]$ $[P_2(3,1)+P_2(3,2)]/[1-P(3,3)]$	(3.7) (3.8)
3	1	$r=G_{min}+g_2$ $g=g_3$	$P(1)P_1(1,1)+P(3)P_1(3,1)]+[P(1)P(1,2)$ $+P(2)+P(3)P(3,2)]P_1(2,1)/[1-P(2,2)]$	
	2	$r=g_2$ $g=g_3$	$P(1)P_2(1,1)+P(3)P_2(3,1)]+[P(1)P(1,2)$ $+P(2)+P(3)P(3,2)]P_2(2,1)/[1-P(2,2)]$	(3.5) (3.6)
	3	$r=G_{min}$ $g=g_3$	$P(1)P_1(1,3)+P(3)P_1(3,3)]+[P(1)P(1,2)$ $+P(2)+P(3)P(3,2)]P_1(2,3)/[1-P(2,2)]$	
	4	$r=0$ $g=g_3$	$P(1)P_2(1,3)+P(3)P_2(3,3)]+[P(1)P(1,2)$ $+P(2)+P(3)P(3,2)]P_2(2,3)/[1-P(2,2)]$	(3.7) (3.8)

where r = effective red time
g = green time

phase 2 have positive effective red times, while Pattern 3 has a zero effective red time. Similarly, Patterns 1, 2, and 3 of phase 3 have positive effective red times, and Pattern 4 has a zero effective red time.

Step 4: Determine Pattern Probabilities. Pattern probability is computed from summing up the product of stationary and transition probabilities of the transitions that produce the concerned pattern. Table 3.1 shows the pattern probabilities of the three phases. The first two patterns of phase 2 are explained below to illustrate how they are obtained.

Pattern 1 has the green time of g_2 and the effective red time of G_{min}. In Figure 3.3, it can be observed that this pattern appears in the following two sub-transitions:

State 2 to state 1, sub-transition 1; and

State 2 to state 2, sub-transition 1.

Since their transition probabilities are $P_1(2,1)$ and $P_1(2,2)$, respectively, and the stationary probability of state 2 is P(2), the pattern probability is $P(2) * P_1(2,1) + P(2) * P_1(2,2)$, i.e., $P(2)[P_1(2,1) + P(_1(2,2)]$.

Pattern 2 is more complicated. Its green time is g_2, and its effective red time is g_3+G_{min}. As observed in Figure 3.3 again, this pattern appears in the following (sub-)transitions:

State 1 to state 1, sub-transition 1;

State 1 to state 2, sub-transition 1;

State 1 to state 3;

State 2 to state 3;

State 3 to state 1, sub-transition 1;

State 3 to state 2, sub-transition 1; and

State 3 to state 3.

This pattern is depicted in Figure 3.4 as separated into three components according to the status in cycle 1: state 1, state 2, and state 3. The pattern probability contributed by each component is shown in the figure, and their sum is the pattern probability.

The third component shows that the pattern appears in the following three transitions:

State 3 to state 1, sub-transition 1;

State 3 to state 2, sub-transition 1; and

State 3 to state 3.

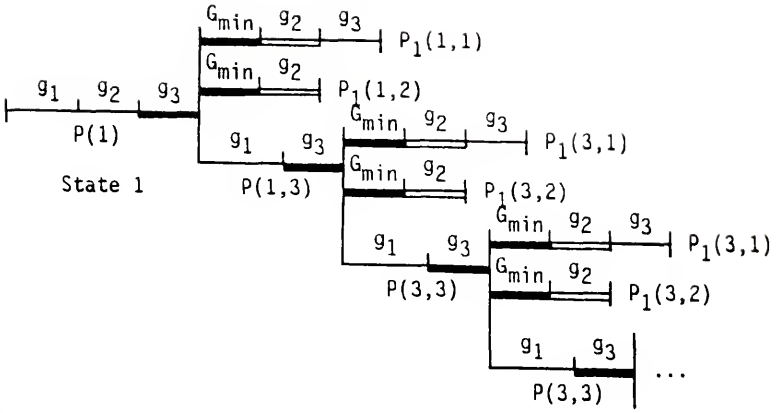
For easy reference, the three transitions are referred to as transitions a, b, and c here. The pattern probability contributed by transitions a and b, as explained above, is

$$P(3)[P_1(3,1) + P_1(3,2)]. \tag{3.24}$$

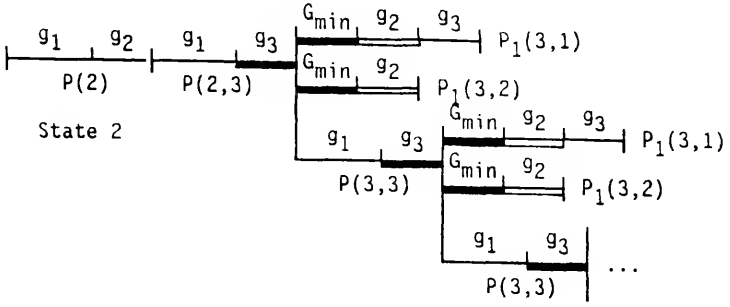
However, the probability contributed by transition c involves an infinitive series. When this transition occurs, the green and effective red times will not appear in the current transition due to phase 2 being skipped. But they may appear in the next transition if the next transition is either transition a or b. The probability of this situation is

$$P(3)P(3,3)[P_1(3,1) + P_1(3,2)]. \tag{3.25}$$

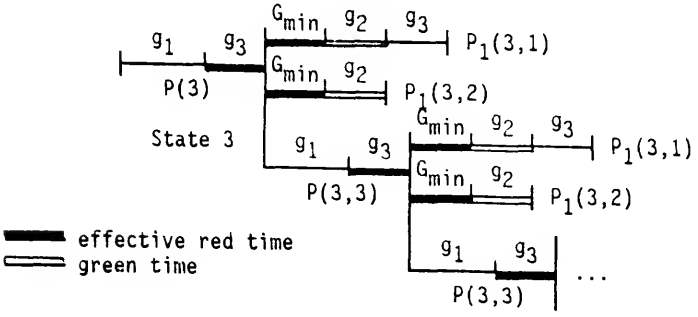
Similarly, if the next transition is c again, then the above situation may repeat and therefore the probability is



Probability=$P(1)[P_1(1,1)+P_1(1,2)]+P(1)P(1,3)[P_1(3,1)+P_1(3,2)]/[1-P(3,3)]$



Probability=$P(2)P(2,3)[P_1(3,1)+P_1(3,2)]/[1-P(3,3)]$



Probability=$P(3)[P_1(3,1)+P_1(3,2)]/[1-P(3,3)]$

Pattern probability=$P(1)[P_1(1,1)+P_1(1,2)]+[P(1)P(1,3)+P(2)P(2,3)+P(3)][P_1(3,1)+P_1(3,2)]/[1-P(3,3)]$

Figure 3.4. Example of the Determination of Pattern Probability.

$$P(3)P(3,3)[P_1(3,1) + P_1(3,2)]$$
$$+ P(3)P(3,3)^2[P_1(3,1) + P_1(3,2)]$$
$$+ P(3)P(3,3)^3[P_1(3,1) + P_1(3,2)]+...$$
$$= P(3)P(3,3)[P_1(3,1) + P_1(3,2)]/[1 - P(3,3)] \quad (3.26)$$

Combining (3.24) and (3.26), the total probability contributed by this component is

$$P(3)[P_1(3,1) + P_1(3,2)] + P(3)P(3,3)[P_1(3,1) + P_1(3,2)]/[1 - P(3,3)]$$
$$= P(3)[P_1(3,1) + P_1(3,2)]\{1 + P(3,3)/[1 - P(3.3)]\}$$
$$= P(3)[P_1(3,1) + P_1(3,2)]/[1 - P(3,3)]. \quad (3.27)$$

The other two components will not be explained since they follow the same logic.

Step 5: Compute Stop Probabilities and Average Delays. By entering r and g of each pattern along with the phase traffic volume to the equations numbered in the last column of Table 3.1, the pattern stop probability and average delay can be computed. Then by applying Equations (3.14) and (3.15), the average delays for the three phases and for the intersection as a whole can be estimated. Similarly, by applying Equations (3.18) and (3.19), the stop probabilities for the three phases and for the intersection as a whole can also be estimated.

Coordinated Control

Under coordinated control, a background cycle length is imposed on each individual signal in order to achieve green bands for progressive movements on the major street. A three-phase signal under coordinated control is presented in this section.

Step 1: Determine Transitions. There are four states in one cycle, based on whether phase 2 or 3 is skipped or not. They are (1) phase 1, then phase 2, and finally phase 3; (2) phase 1 followed by phase 2, then

returns to phase 1; (3) phase 1 followed by phase 3, then returns to phase 1; and (4) phase 1 only. State 1 is the normal sequence, in which no actuated phase is skipped. State 2 is the case that phase 3 is skipped due to lack of demand before phase 2 completes. State 3 means that phase 2 is skipped, but phase 3 is not. State 4 indicates that both phases 2 and 3 are skipped, so that the green light stays on phase 1 to complete the whole cycle. The sixteen transitions constituted by the four states are shown in Figure 3.5.

It can be seen in states 2 and 3 that the green light returns to phase 1 to complete the cycle after the activated phase (either phase 2 or phase 3) has been serviced. The time interval beyond the end of the last activated phase to the end of one cycle is called slack time. The maximum slack time, as can be observed in state 4 in which both phases 2 and 3 are skipped, is the cycle length minus G_{min}.

Moreover, as shown in transitions 4, 8, 12, and 16, both phases 2 and 3 are skipped in cycle 2, since they are not activated before G_{min} completes. In this case, if a vehicle arrives for phase 3 right after the end of G_{min}, the vehicle has to wait till the next cycle to be serviced. This is certainly not efficient. Some commercial controllers use permissive periods to improve this situation. A permissive period in this example would allow phase 3 to receive the green time in cycle 2, if activated after the end of G_{min}, but before the end of the permissive period. To accomplish this, transitions 4, 8, 12, and 16 would have to be split into several further transitions, to represent all the possible outcomes. Since permissive periods greatly increase the complexity of the analysis, they will not be considered in this example.

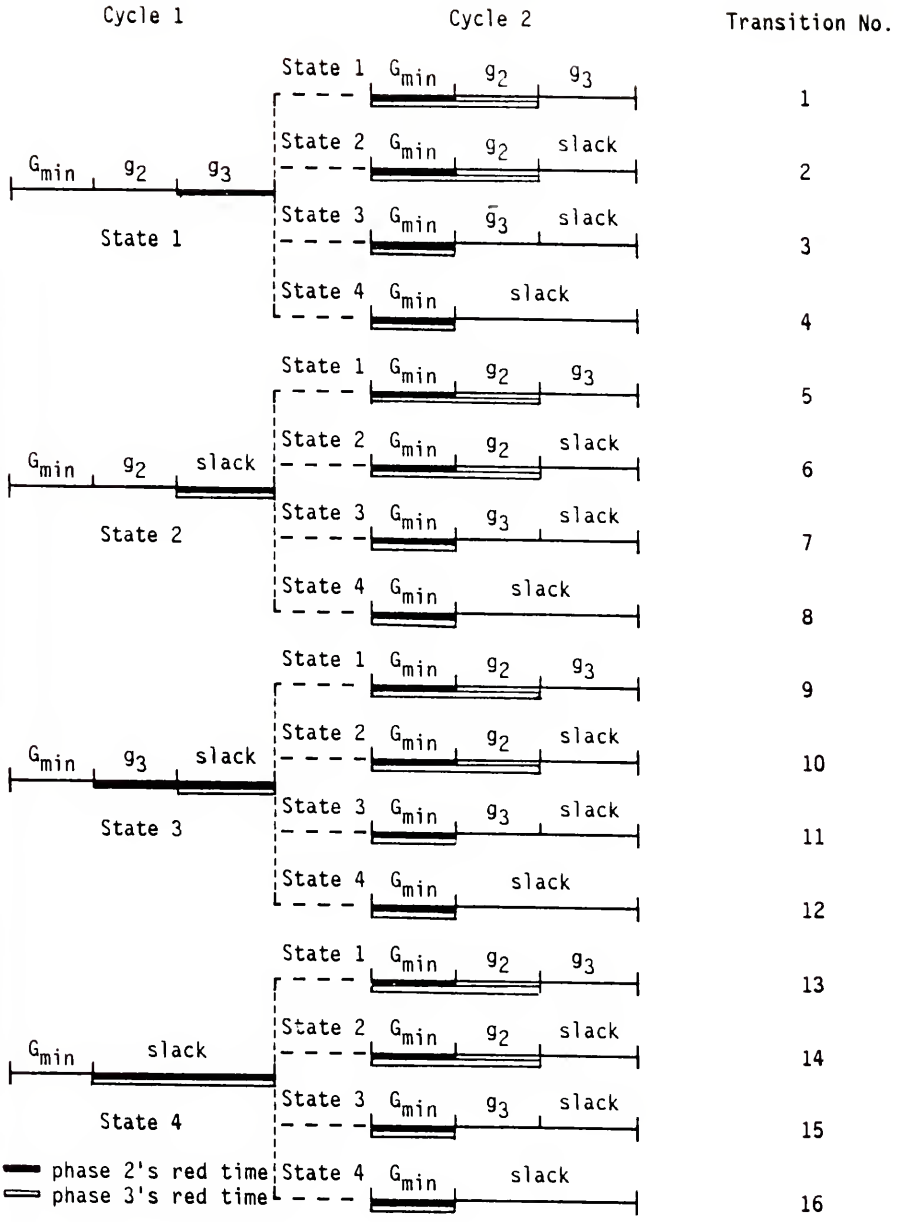


Figure 3.5. Transitions, Red Times, and Transition Probabilities at a Three-Phase Semi-Actuated Signal Under Coordinated Control.

Transition No.	Transition probability
1	$P(1,1)=\{1-\exp[-v_2(g_3+G_{min})]\}\{1-\exp[-v_3(G_{min}+g_2)]\}$
2	$P(1,2)=\{1-\exp[-v_2(g_3+G_{min})]\}\exp[-v_3(G_{min}+g_2)]$
3	$P(1,3)=\exp[-v_2(g_3+G_{min})][1-\exp(-v_3G_{min})]$
4	$P(1,4)=\exp[-v_2(g_3+G_{min})]\exp(-v_3G_{min})$
5	$P(2,1)=\{1-\exp[-v_2(g_3+G_{min})]\}\{1-\exp[-v_3(g_3+G_{min}+g_2)]\}$
6	$P(2,2)=\{1-\exp[-v_2(g_3+G_{min})]\}\exp[-v_3(g_3+G_{min}+g_2)]$
7	$P(2,3)=\exp[-v_2(g_3+G_{min})]\{1-\exp[-v_3(g_3+G_{min})]\}$
8	$P(2,4)=\exp[-v_2(g_3+G_{min})]\exp[-v_3(g_3+G_{min})]$
9	$P(3,1)=\{1-\exp[-v_2(g_3+g_2+G_{min})]\}\{1-\exp[-v_3(g_2+G_{min}+g_2)]\}$
10	$P(3,2)=\{1-\exp[-v_2(g_3+g_2+G_{min})]\}\exp[-v_3(g_2+G_{min}+g_2)]$
11	$P(3,3)=\exp[-v_2(g_3+g_2+G_{min})]\}\{1-\exp[-v_3(g_2+G_{min})]\}$
12	$P(3,4)=\exp[-v_2(g_3+g_2+G_{min})]\}\exp[-v_3(g_2+G_{min})]$
13	$P(4,1)=\{1-\exp[-v_2(g_2+g_3+G_{min})]\}\{1-\exp[-v_3(g_2+g_3+G_{min}+g_2)]\}$
14	$P(4,2)=\{1-\exp[-v_2(g_2+g_3+G_{min})]\}\exp[-v_3(g_2+g_3+G_{min}+g_2)]$
15	$P(4,3)=\exp[-v_2(g_2+g_3+G_{min})]\}\{1-\exp[-v_3(g_2+g_3+G_{min})]\}$
16	$P(4,4)=\exp[-v_2(g_2+g_3+G_{min})]\}\exp[-v_3(g_2+g_3+G_{min})]$

Figure 3.5. — continued.

Step 2: Compute Transition and Stationary Probabilities. The transition probabilities are shown in Figure 3.5. Similarly to isolated control, stationary probabilities, P(i), i=1 to 4, can be obtained from solving the following equations:

$$[\ P(1),P(2),P(3),P(4)\ ] \begin{bmatrix} P(1,1) & P(1,2) & P(1,3) & P(1,4) \\ P(2,1) & P(2,2) & P(2,3) & P(2,4) \\ P(3,1) & P(3,2) & P(3,3) & P(3,4) \\ P(4,1) & P(4,2) & P(4,3) & P(4,4) \end{bmatrix} = \begin{bmatrix} P(1) \\ P(2) \\ P(3) \\ P(4) \end{bmatrix} \quad (3.28)$$

with P(1)+P(2)+P(3)+P(4)=1.

Steps 3 and 4.

Since the processes of Steps 3 (Determine patterns) and 4 (Determine pattern probabilities) are similar to those under isolated control, only their results are shown in Table 3.2.

Step 5: Compute Stop Probabilities and Average Delays. The processes of this step to arrive at phase and intersection stop probabilities and average delays are similar to those under isolated control. But the effect of progression on phase 1 should be further considered.

Up to this point, the stop probabilities and average delays obtained assume Poisson arrival conditions. As stated in the section of Assumptions and Notations, the non-actuated phase (i.e., phase 1, which controls the major street traffic) is assumed to be under the influence of traffic progression from the upstream intersection. Hence, the stop probability and average delay of phase 1 should be further adjusted to take this factor into account. As reviewed in Chapter Two, the influence of traffic progression can be accessed by using the progression adjustment factors (PF) provided in the 1985 Highway Capacity Manual (HCM) [19]. The stop probability and average delay for

Table 3.2. Patterns (in Terms of Red and Green Times) and Their Probabilities at a Three-Phase Semi-Actuated Signal Under Coordinated Control.

Phase	Pat.	Type of pattern	Pattern probability	Ps and d equations
1	1	$r=g_2+g_3$ $g=G_{min}$	$P(1)[P(1,1)+P(1,2)+P(1,3)]$	
	2	$r=g_2$ $g=G_{sla2}+G_{min}$	$P(2)[P(2,1)+P(2,2)+P(2,3)]$	
	3	$r=g_3$ $g=G_{sla2}+G_{min}$	$P(3)[P(3,1)+P(3,2)+P(3,3)]$	(3.3)
	4	$r=g_2+g_3$, n=2,3,... $g=(n-1)C_B+G_{min}$, n=2,3,...	$P(1)[P(4)+P(1,4)]P(4,4)^{n-2}$ $[P(4,1)+P(4,2)+P(4,3)]$	(3.4)
	5	$r=g_2$ $g=nC_B-g_2$, n=2,3,...	$P(2)[P(4)+P(2,4)]P(4,4)^{n-2}$ $[P(4,1)+P(4,2)+P(4,3)]$	
	6	$r=g_3$ $g=nC_B-g_3$, n=2,3,...	$P(3)[P(4)+P(3,4)]P(4,4)^{n-2}$ $[P(4,1)+P(4,2)+P(4,3)]$	

where $G_{sla2} = g_2$
$G_{sla3} = g_3$
r = red time
g = green time

Table 3.2. — continued.

Phase	Pat.	Type of pattern	Pattern probability	Ps and d equations
2	1	$r=g_3+G_{min}$ $g=g_2$	$P(1)[P(1,1)+P(1,2)]$	
	2	$r=G_{sla3}+G_{min}$ $g=g_2$	$P(2)[P(2,1)+P(2,2)]$	(3.5)
	3	$r=g_3+G_{sla2}+G_{min}$ $g=g_2$	$P(1)P(1,3)+P(2)P(2,3)+P(4)P(4,3)$ $+P(3)[P(3,1)+P(3,2)+P(3,3)]$	(3.6)
	4	$r=G_{sla}+G_{min}$ $g=g_2$	$P(1)P(1,4)+P(2)P(2,4)+P(3)P(3,4)$ $+P(4)[P(4,1)+P(4,2)+P(4,4)]$	
3	1	$r=G_{min}+g_2$ $g=g_3$	$P(1)P(1,1)$	
	2	$r=G_{min}$ $g=g_3$	$P(1)P(1,3)$	
	3	$r=G_{sla2}+G_{min}+g_2$ $g=g_3$	$P(3)P(3,1)+\{P(1)[P(1,2)+P(1,4)P(5,2)]+$ $P(2)+P(3)[P(3,2)+P(3,4)P(5,2)+P(4)$ $P(4,2)\}P(2,1)/\{1-[P(2,2)+P(2,4)P(4,2)]\}$	(3.5)
	4	$r=G_{sla2}+G_{min}$ $g=g_3$	$P(3)P(3,3)+\{P(1)[P(1,2)+P(1,4)P(5,2)]+$ $P(2)+P(3)[P(3,2)+P(3,4)P(5,2)+P(4)$ $P(4,2)\}P(2,3)/\{1-[P(2,2)+P(2,4)P(4,2)]\}$	(3.6)
	5	$r=G_{sla}+G_{min}+g_2$ $g=g_3$	$\{P(1)[P(1,4)+P(1,2)P(5,4)]+P(2)[P(2,4)+$ $P(2,2)P(5,4)+P(3)[P(3,4)+P(3,2)P(5,4)+$ $+P(4)\}P(4,1)/\{1-[P(4,4)+P(4,2)P(2,4)]\}$	
	6	$r=G_{sla}+G_{min}$ $g=g_3$	$\{P(1)[P(1,4)+P(1,2)P(5,4)]+P(2)[P(2,4)+$ $P(2,2)P(5,4)+P(3)[P(3,4)+P(3,2)P(5,4)+$ $+P(4)\}P(4,3)/\{1-[P(4,4)+P(4,2)P(2,4)]\}$	

where $G_{sla2} = g_2$
$G_{sla3} = g_3$
$G_{sla} = g_2+g_3$
$P(5,2) = P(4,2)/[1-P(4,4)]$
$P(5,4) = P(2,4)/[1-P(2,2)]$
r = effective red time
g = green time

phase 1, computed by this method, are multiplied by PF to account for the influence of traffic progression. Since the determination of PF values has been reviewed in Chapter Two, it will not be repeated here. The PF values are simply regarded as input in this method.

Test of the Analytical Method

Since the quantitative analysis of average delays and stop probabilities is very complicated, some approximations are used in the development of this method. Justification is needed for these approximations. A simulation which deals with individual vehicles in determining delays and stops was employed for this justification. The purpose of this simulation is to test, under the same assumptions, whether the Analytical Method will produce the same results as does the simulation. If the results are close, it would be reasonable to conclude that the mathematics in this method is correct.

It should be emphasized, however, that this simulation is simply to test the mathematical model in this method under the previously stated assumptions. Field data would be required to further validate whether the assumptions are reasonable.

It would be best to test the mathematical model if existing simulation programs can be used. NETSIM [31] could be a reasonable choice for this purpose, since it is the most widely used simulation program in the traffic engineering community. However, NETSIM assumes uniform arrivals on entry links, but the Analytical Method assumes Poisson arrivals. Therefore, they are not under the same assumptions. Because of the difference in the underlying assumptions, NETSIM could not be used and a new simulation program was developed.

Since the Analytical Method is conducted on an intersection basis, the simulation deals with only individual intersections. Also, since the Analytical Method originally computes average delays and stop probabilities with no consideration of progression (though it then uses the HCM's progression adjustment factors to account for the effect of progression on the non-actuated phase), the simulation does not simulate platoon arrivals either. Only random flows are simulated, regardless of whether the signal is under coordinated control or isolated control. The results from the two methods, before the adjustments for progression, are compared in this section.

In the simulation program, a sequence of vehicle arrival times for each actuated phase is first generated, with exponentially distributed inter-arrival times. These arrival times represent the times of vehicle arrivals at the stop line (which also represent the detection times, since a presence detector is presumed to be located near the stop line). The mechanics of the semi-actuated signal operations are built into the program to determine the start times of the green phase of each actuated phase. For example, for coordinated operation, the program first checks if the first actuated phase has any arrivals up to the yield point. If it does, the actuated phase is given green time right after the yield point, and the program checks if the second actuated phase registers any arrivals up to the end of the green time of the first actuated phase. On the other hand, if the first actuated phase does not have any arrivals up to the yield point, it is skipped and the program checks if the second actuated phase has any arrivals up to the yield point. If the second actuated phase also has no arrivals, the next actuated phase

is checked. After all the actuated phases have been checked, one cycle is completed, and the program starts the next cycle.

The queued vehicles arriving in the red time of an actuated phase, and those (if any) arriving before the queue has fully discharged, are released at the saturation flow rate. The moment a vehicle is released represents the departure time of the vehicle leaving the stop line. The delay of each stopped vehicle was calculated as the departure time minus the arrival time. The average delay per vehicle was calculated as the total delay divided by the total number of vehicles, with total delay as the sum of the delay of all stopped vehicles. The stop probability was obtained by dividing the total number of vehicles stopped by the total number of vehicles. Isolated and coordinated controls were treated separately.

From the above description, it can be seen that vehicle arrival times of actuated phases are the only random variables generated in the simulation process. After they are generated, the remaining processes are deterministic based on these arrival times, the signal operation, and the saturation departure rate.

A three-phase signal was simulated under both isolated and coordinated controls. The minimum green time of the non-actuated phase and the green times of the actuated phases were taken as 20 seconds. Under each kind of control, 216 sets of volumes were tested—the three phases were given volumes from 50 vehicles per hour (vph) to 300 vph, with 50 vph increments. Each set of volumes was simulated for ten replications, and each replication was simulated for 6,000 seconds.

The Analytical Method was coded into a computer program to compute stop probabilities and average delays for the 216 sets of volumes. Part

of the results are shown in Figure 3.6, which presents four comparisons: stop probabilities and average delays of phase 2 under both isolated and coordinated controls, when phase 3's volume is 50 vph. The average delays obtained from simulation runs are plotted to illustrate both the central tendency and the dispersion, but only the central tendency of stop probabilities are plotted, since their standard deviations are very small (less than 0.3%). These comparisons show that the estimations from the method are visually fitted to the data points obtained from simulation runs. Since other sets of results show the same pattern, they are omitted. This finding indicates that the approximations in this method are acceptable.

Comparison with a Pretimed Model

According to the review in Chapter Two, very few models exist which deal exclusively with semi-actuated signal evaluation. A common evaluation practice, given this lack of appropriate models, is the use of a model for pretimed signals, with average green and red times as input. The purpose of this section is to investigate the difference between using a pretimed model and using the Analytical Method. The method using a pretimed model will be referred to as the Pretimed Model Method, in contrast to the Analytical Method.

The three-phase signal is used again in this comparison, as it was used in the previous section for validation against simulation. Recall that the minimum green time of the non-actuated phase and the green times of the two actuated phases are taken as 20 seconds. Because an actuated phase has 20 seconds of green time when present, but has zero seconds of green time when skipped, and because the phase's red time depends on the presence of the other actuated phase, it is very

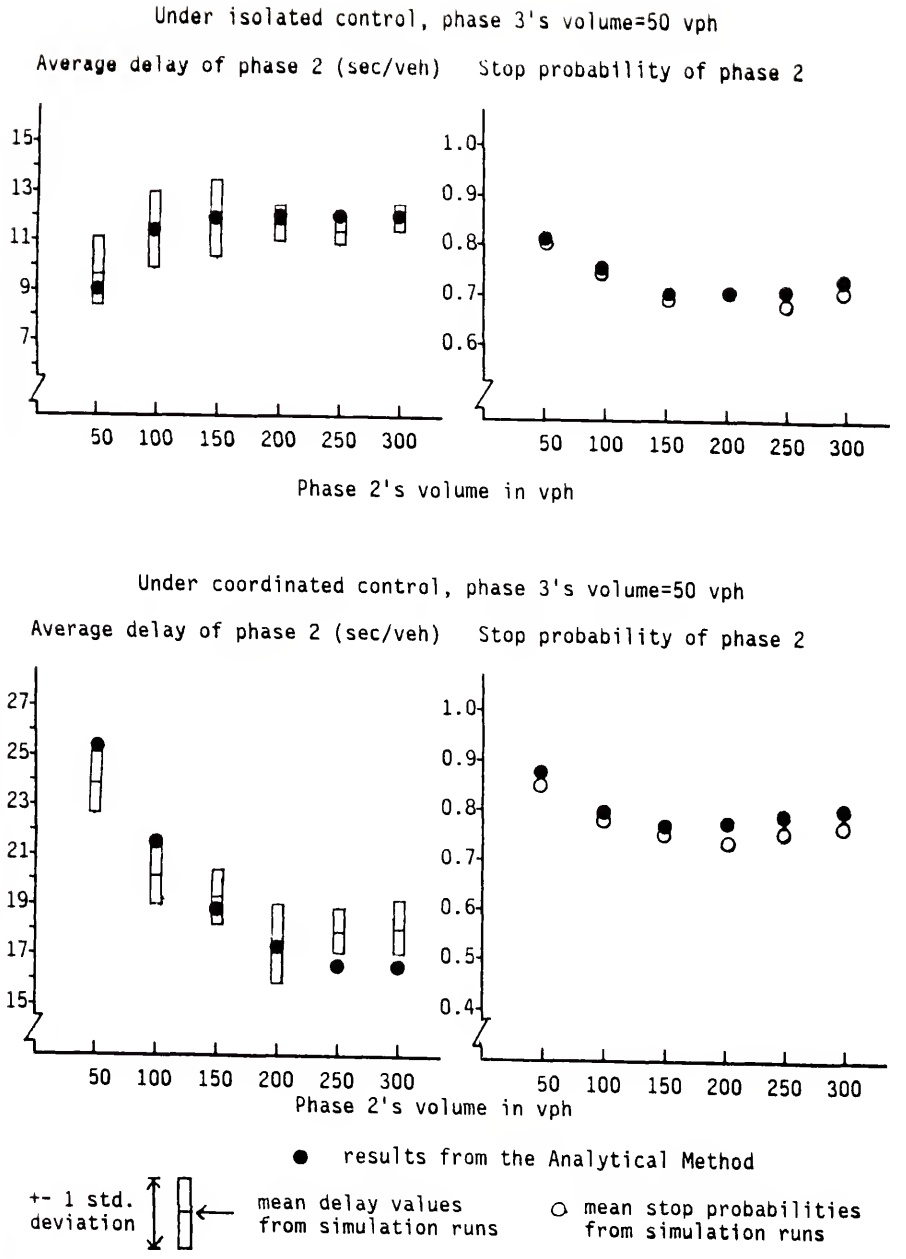


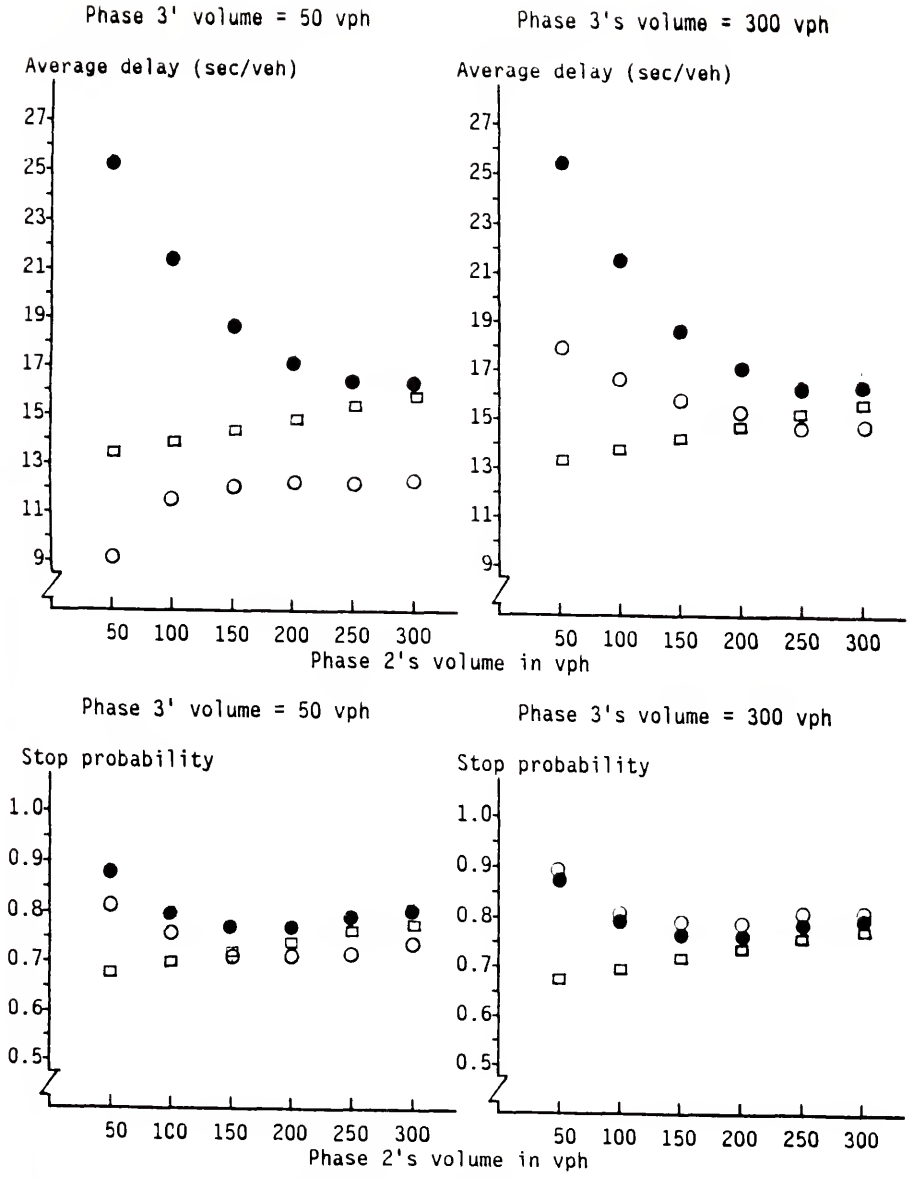
Figure 3.6. Stop Probability and Average Delay Comparisons, the Analytical Method vs. Simulation.

difficult to estimate the phase's average red and green times without conducting a field observation or performing a simulation. For simplicity, it is assumed that the average green time of each phase is 20 seconds. In other words, the three phases are assumed to appear in every cycle with 20 seconds of green time. Under this assumption, each phase has a red time of 40 seconds and a green time of 20 seconds in each cycle.

Since Equations (3.3) and (3.4) are for pretimed phases, they are used in the Pretimed Model Method to compute the stop probabilities and average delays for phase 2 of the above pretimed signal. The stop probabilities and average delays of phase 2 when phase 3's volumes are 50 vph and 300 vph are shown in Figure 3.7. In this figure, the results from the two methods show some differences. The deviations are highly significant at very low volumes (such as less than 150 vph), but they are small when volumes of both phases 2 and 3 approach 300 vph.

One observation stands out clearly in this figure, which is that the Pretimed Model Method is unable to differentiate isolated and coordinated controls. In the Analytical Method, isolated and coordinated controls yield different stop probabilities and average delays. But the two different controls yield the same results in the Pretimed Model Method.

The different results can be explained by investigating the intermediate results from the Analytical Method. The intermediate results from this method are shown in Table 3.3 for phase 2 under coordinated control, with phase 2 having a volume of 150 vph, and phase 3 of 300 vph. In Table 3.3 (a), there are four patterns, which fall into two types of cycles. The first two patterns have a red time of 40



● results from the Analytical Method, under coordinated control
○ results from the Analytical Method, under isolated control
□ results from the Pretimed Model Method

Figure 3.7. Stop Probability and Average Delay Comparisons, the Analytical Method vs. the Pretimed Model Method.

Table 3.3. A Further Comparison Between the Analytical Method and the Pretimed Model Method.

(a) Results from the Analytical Method, under coordinated control (Phase 2's volume=150 vph, phase 3's volume=300 vph)

Phase	Pat.	Type of pattern (sec.)	Pattern prob.	Pattern stop prob.	Pattern avg. delay (sec/veh)
2	1	$r=g_3+G_{min}=40$ $g=g_2=20$	0.653	0.779	16.57
	2	$r=G_{sla3}+G_{min}=40$ $g=g_2=20$	0.020	0.779	16.57
	3	$r=g_3+G_{sla2}+G_{min}=60$ $g=g_2=20$	0.271	0.833	24.11
	4	$r=G_{sla}+G_{min}=60$ $g=g_2=20$	0.056	0.833	24.11
Phase stop probability				0.80	
Phase average delay (sec/veh)				19.54	

(b) Results from the Pretimed Model Method (phase 2's volume=150 vph)

Phase Red time (sec)	Phase Green time (sec)	Phase stop probability	Phase average delay (sec/veh)
40	20	0.727	14.55

seconds and a green time of 20 seconds, while the last two patterns have a red time of 60 seconds and a green time of 20 seconds. As explained previously (with the aid of Figure 3.5), the second cycle type results from phase skipping. The pattern probabilities in Table 3.3 (a) show that 67.3% of cycles are of the first type, while 32.7% of cycles are of the second type. In comparison, the Pretimed Model Method treats all the cycles as the first cycle type, since it has no way to figure out what percentage will be of the second cycle type. In other words, the Pretimed Model Method is unable to handle phase skipping.

Furthermore, the stop probability and average delay in the first cycle type are different in the Analytical Method from those computed in the Pretimed Model Method. This is because the Analytical Method uses equations which were developed by considering phase skipping and dwelling. The equations used in the Pretimed Model Method, however, do not have the capability to handle phase skipping and dwelling.

From the above discussions, it can be seen that the deviation of the two methods' results is due to the inability of the Pretimed Model Method to deal with phase skipping and dwelling. Thus, models for pretimed phases are not applicable for actuated phases under low volume conditions.

Summary and Discussions

This chapter presents the Analytical Method to estimate stop probabilities and average delays for semi-actuated signals at low volumes, under both isolated and coordinated controls. The method investigates various cycle patterns, and computes their probabilities using Markov chain recurrence and the Poisson distribution. The method is validated against simulation, confirming that the mathematics in the

method is correct. Stop probability and average delay from this method are compared to those from a model for pretimed signals. The comparisons show that when traffic volumes approach 300 vph, they are close. When traffic volumes are much lower than 300 vph, the difference is significant.

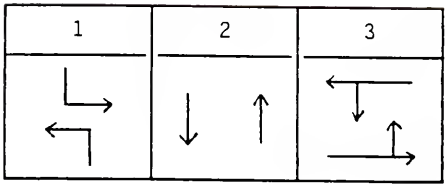
The method is easy to apply when there are only two phases. When the number of phases increases, the complexity increases significantly. For instance, a four-phase signal (one non-actuated phase and three actuated phases) under isolated control has $2^3 - 1 = 7$ states in one cycle. Hence, there are total of $2 * 7^2 = 98$ sub-transitions to consider.

The method is capable of handling single ring operations without overlap, but it would be too involved to deal with either dual ring or overlap situations. The difference between single and dual rings is illustrated in Figure 3.8. Figure 3.8 (a) is a single ring operation without overlap, which is characterized as having each movement appear in only one phase. Figure 3.8 (b) is a dual ring operation with overlap, in which phase 1 may change to any of phases 2, 3 or 4, depending on the traffic demand of those three phases.

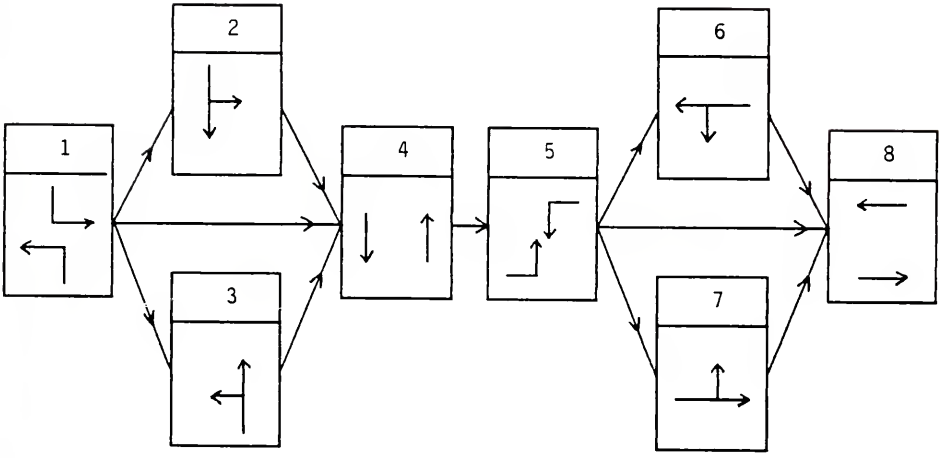
Because of these disadvantages, a second method is considered using a macroscopic approach. The second method, which is presented in the next chapter, does not analyze the various situations of individual cycles. Instead, it uses average red and green times.

Equations Development

This section develops the stop probability and average delay equations used in this chapter. The non-actuated phase is treated first.



(a) Single ring operation without overlap



(b) Dual ring operation with overlap

Figure 3.8. Actuated Signal Operation Examples of Single Ring without Overlap and Dual Ring with Overlap.

The Non-Actuated Phase

Since the non-actuated phase appears in every cycle, regardless of whether it has traffic demand or not, it generally acts like a pretimed phase, except that its red and green lengths may vary from cycle to cycle. For given red and green times, the non-actuated phase can be regarded as a pretimed phase. Hence, the stop probability and average delay equations for pretimed phases can be applied to the non-actuated phase.

Although a variety of stop probability and average delay equations have been proposed for pretimed signals, the ones used in the HCM [19], SOAP [52], or TRANSYT [45] are most popular. Since Hagen and Courage [17] have demonstrated that their models agree closely at volume levels below the saturation point, the stop probability equation used in SOAP and the average delay equation used in TRANSYT are adopted in this study. For convenience, the two equations are shown in the following:

$$Ps = \frac{1 - g/C}{1 - xg/C} \tag{3.29}$$

$$d = d1 + d2 \tag{3.30}$$

$$= \frac{C(1 - g/C)^2}{2(1 - xg/C)} + \left[\left(\frac{Bn}{Bd}\right)^2 + \frac{x^2}{Bd}\right]^{1/2} - \frac{Bn}{Bd}$$

where $C = r + g$

$$Bn = 2(1 - x) + \frac{x^2}{1800v}$$

$$Bd = \frac{4x}{1800v} - \left(\frac{x}{1800v}\right)^2$$

Equation (3.29) can be derived to another form for easy application.

$$Ps = \frac{1 - g/C}{1 - xg/C}$$

$$= \frac{C(1 - g/C)}{C(1 - xg/C)}$$

$$= \frac{C - g}{C(1 - v/s)}$$

$$= \frac{rs}{C(s - v)}$$

$$= \frac{r}{C}\left(1 + \frac{v}{s - v}\right)$$

$$= \frac{1}{r + g}\left(r + \frac{rv}{s - v}\right)$$

$$= \frac{r + g_s}{r + g} \qquad (3.31)$$

where $g_s = \frac{rv}{s - v}$ (3.32)

Equation (3.31) means that the stop probability is the sum of the red and saturation green times divided by the cycle length. This form is consistent with the intuition, since a vehicle will be stopped if it arrives either in the red time or in the saturation green time joining the end of a discharging queue. Hence, the stop probability is the proportion of the sum of the red and saturation green times to the cycle length.

Equation (3.30) consists of two terms, d1 and d2. The first term represents the average delay per vehicle under the assumption of uniform arrivals with an average arrival rate of v throughout the cycle. The second term is often called random delay or overflow delay since it

attempts to account for the fact that the vehicles arrive randomly [24]. The second term can be verified to be very small relative to the first term when traffic volume is less than 300 vph. Hence, the second term can be neglected under low volume conditions.

The first term of Equation (3.30) can also be derived to another form for easy application.

$$d1 = \frac{C(1 - g/C)^2}{2(1 - xg/C)}$$

$$= \frac{C(1 - g/C)}{1 - xg/C} \frac{C(1 - g/C)}{2}$$

$$= \frac{r + g_s}{r + g} \frac{C - g}{2}$$

$$= \frac{r + g_s}{r + g} \frac{r}{2} \tag{3.33}$$

$$= \frac{r}{2} Ps \tag{3.34}$$

Moreover, since Equation (3.34) is approach delay, it is divided by 1.3 to reflect only the stopped delay portion of the total approach delay [19].

$$d1 = \frac{r}{2.6} Ps \tag{3.35}$$

Equation (3.35) means that the average delay is the red time multiplied by the stop probability, and then divided by 2.6.

Equations (3.31), (3.32), and (3.35) are used in the Analytical Method as Equations (3.3), (3.9), and (3.4), respectively.

Recall that uniform arrivals with an average rate of v throughout the cycle are assumed in Equations (3.31), (3.32), and (3.35). Thus,

the number of vehicle arrivals is proportional to the length of red time. But this property is not always true for actuated phases.

Actuated Phases

Unlike the non-actuated phase appearing in every cycle, an actuated phase receives green time only after it is activated by a vehicle arrival. After the actuated phase is activated, it may receive green time immediately, depending on whether dwell is occurring or not. The actuated phase will receive green time immediately if the green light is dwelling on the non-actuated phase. Otherwise, the actuated phase will have to wait to receive green time. In the former case, there is only one arrival, which triggers the end of the red time, regardless of how long the red time has been. In the latter case, the actuation(s) may occur at any point of the red time. In this case, similarly to pretimed or non-actuated phases, a longer red time can be assumed to include more arrivals. Because of the difference between the two cases, red time is not applicable in calculating arrivals. Effective red time (which subtracts the red time without arrivals from the actual red time) is used to substitute for the actual red time for actuated phases. It is clear that effective red time is zero when the actuated phase terminates the dwell; otherwise, the effective red time is the same as the actual red time. The equation development is also split into the two situations.

Positive Effective Red Times Consider a model which has a cyclic time period with two components r and g. R represent a red time, but g can be red or green depending on whether the actuated phase is activated in r or not. If a vehicle arrives in r, g will be green; otherwise, if no vehicle arriving in r, g remains red.

First of all, let's consider stop probability. A vehicle can arrive either in r or g. For a given vehicle, the probability of arriving in r is r/(r + g), and the probability of arriving in g is g/(r + g). Hence, the stop probability of the vehicle is

$$Ps = \frac{r}{r+g}(Ps \text{ in } r) + \frac{g}{r+g}(Ps \text{ in } g) \tag{3.36}$$

Where (Ps in r) and (Ps in g) denote the stop probability of the vehicle arriving in r and in g, respectively. When the vehicle arrives in r, it will be stopped, i.e.,

$$(Ps \text{ in } r) = 1 \tag{3.37}$$

When the vehicle arrives in g, there are two possibilities. If there is no other vehicle arriving in r, g will be red, and the vehicle will be stopped. The probability of this possibility is e^{-vr}. In the other possibility, if any vehicles have arrived in r, g will be green. The probability of this possibility is $(1 - e^{-vr})$. When this occurs, there are two sub-situations: either (1) the vehicle arrives in the saturation green time (g_s), or (2) the vehicle arrives in the remaining green time ($g - g_s$). The probability of sub-situation (1) is g_s/g and the vehicle will be stopped (since the vehicle will join the end of the dissipating queue), i.e., Ps = 1. The probability of sub-situation (2) is

$$(g - g_s)/g,$$

but the vehicle will not be stopped (since the queue has already dissipated), i.e., Ps = 0. In conclusion, the stop probability of the vehicle arriving in g is

$$(\text{Ps in g}) = e^{-vr}\ 1 + (1 - e^{-vr})\ [\ \frac{g_s}{g}\ 1 + \frac{g - g_s}{g}\ 0\ ]$$

$$= e^{-vr} + (1 - e^{-vr})\ \frac{g_s}{g} \qquad (3.38)$$

Substituting (3.37) and (3.38) into (3.36), the stop probability is

$$Ps = \frac{r}{r + g}\ 1 + \frac{g}{r + g}\ [\ e^{-vr} + (1 - e^{-vr})\ \frac{g_s}{g}\ ]$$

$$= \frac{r + g_s}{r + g} + \frac{g - g_s}{r + g}\ e^{-vr}$$

$$= \frac{r + g_s}{r + g} + (1 - \frac{r + g_s}{r + g})\ e^{-vr}$$

$$= e^{-vr} + (1 - e^{-vr})\ \frac{r + g_s}{r + g} \qquad (3.39)$$

Equation (3.39) can be further examined by investigating the extremes. When v approaches zero, Ps approaches unity because e^{-vr} approaches unity. This result is consistent with intuition. Remember that any vehicles arriving in the unsaturated green time will not be stopped. When traffic demand is very low, vehicle arrivals are generally sparsely distributed, so that almost every vehicle will arrive in a red time, and very few will follow immediately to arrive in the green time. Hence, the stop probability is close to unity. On the other hand, when v is high, Ps approaches $(r + g_s)/(r + g)$ because e^{-vr} approaches zero. In this case, the actuated phase will be activated in almost every cycle, like the pattern of a pretimed phase. Hence, the stop probability will approach that of a pretimed phase.

Average delay can be estimated by the similar fashion. Since the average delay per vehicle can be regarded as the total delay experienced

by any vehicle, the equation will be developed by considering one vehicle.

A vehicle can arrive either in r or g. For a given vehicle, the probability of arriving in r is r/(r + g), and the probability of arriving in g is g/(r + g). Hence, the total delay of the vehicle is

$$d = \frac{r}{r+g} (d \text{ in } r) + \frac{g}{r+g} (d \text{ in } g) \tag{3.40}$$

Where (d in r) and (d in g) denote the expected waiting time of the vehicle arriving in r and in g, respectively. When the vehicle arrives in r, its expected waiting time is half the red time, i.e.,

$$(d \text{ in } r) = r/2 \tag{3.41}$$

When the vehicle arrives in g, there are two possibilities. If there is no other vehicle arriving in r, g will be red, and the vehicle will have to wait till the next cycle. Its expected waiting time is half of g plus r, i.e., r + g/2. The probability of this possibility is e^{-vr}. In the other possibility if any vehicles have arrived in r, g will be green. When this occurs, there are two sub-situations: either (1) the vehicle arrives in the saturation green time (g_s), or (2) the vehicle arrives in the remaining green time ($g - g_s$). The probability of sub-situation (1) is g_s/g and the expected waiting time of this sub-situation is $g_s/2$. The probability of sub-situation (2) is

$$(g - g_s)/g,$$

but the vehicle will not be delayed (since the queue has already dissipated), i.e., d = 0. Combining these two sub-situations, the expected waiting time of the vehicle arriving in g is

$$(d \text{ in } g) = e^{-vr} \left(\frac{g}{2} + r\right) + (1 - e^{-vr}) \frac{g_s}{g} \frac{g_s}{2} \tag{3.42}$$

Substituting (3.41) and (3.42) into (3.40), the average delay is

$$d = \frac{r}{r+g}\frac{r}{2} + \frac{g}{r+g}\left[e^{-vr}\left(\frac{g}{2} + r\right) + (1 - e^{-vr})\frac{g_s^2}{2g}\right]$$

$$= \frac{r^2}{2(r+g)} + e^{-vr}\frac{g(g+2r)}{2(r+g)} + (1 - e^{-vr})\frac{g_s^2}{2(r+g)} \qquad (3.43)$$

Please note that approximations are used in the equation development. A good example of approximations is the treatment of the saturation green time (g_s). The saturation green time is the first portion of the green time, during which the vehicular queue is discharging. Conversely, the remaining green time is called the unsaturation green time (g_u), during which the queue has been fully discharged, and the arriving vehicle passes the intersection without being stopped or delayed.

The approximation can be better explained by the aid of a typical queue length diagram as illustrated in Figure 3.9. In this figure, g_s is further split into two parts: g_{s1} and g_{s2}. The g_{s1} is the time to discharge the queue accumulated in r, while g_{s2} is the time to discharge the additional vehicles arriving in the green time and joining the end of the moving queue. In the extreme case if the vehicle arrives at the beginning of r, it will be released at the beginning of g. Conversely, if the vehicle arrives at the end of r, it will be released at the end of g_{s1}. Therefore, the expected waiting time for a vehicle arriving in r is more than r/2, but for simplicity, only r/2 is used in Equation (3.40).

When the vehicle arrives in g_s, it will be released in g_{s2}. In the extreme case if the vehicle arrives at the beginning of g_s, it will be released at the beginning of g_{s2}. If the vehicle arrives at the end of

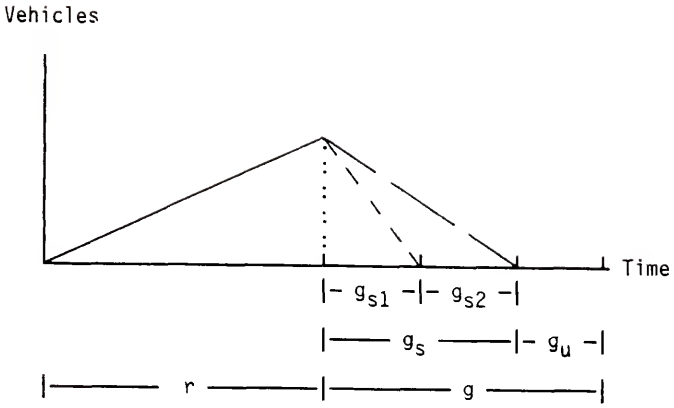


Figure 3.9. Queue Length Example at a Signalized Intersection.

g_s, it will have no delay. Hence, the expected waiting time for a vehicle arriving in g_s is less than $g_s/2$, but for simplicity, $g_s/2$ is used in Equation (3.40).

The error due to the above simplified treatment for g_s is expected to be small for two reasons. The first is that the two errors will be counterbalanced. The second is that the saturation green time is usually very short under low volume conditions.

Equations (3.39) and (3.43) are used in the method as Equations (3.5) and (3.6), respectively.

Zero Effective Red Time Zero effective red time refers to the situation where the actuated phase terminates the dwell. When this occurs, the vehicle which activates the actuated phase will come to a stop and experience a delay of yellow time of the non-actuated phase plus some lost time. Since lost and yellow times are not considered in this method, the vehicle is treated as stopped without any delay. Moreover, since any further vehicles arriving in the green time also have no delay, the average delay is

$$d = 0 \tag{3.44}$$

Based on the same reasoning, the vehicle which terminates the dwell is the only one stopped in this phase. Since the stop rate depends on the total number of vehicles in the phase, and only the first vehicle is stopped, the probabilities of all possible numbers of vehicles arriving in the green time must be considered in order to arrive at the stop probability.

Assuming Poisson arrivals, the probability of i vehicles arriving in the green time (g) is

$$\frac{(vg)^i e^{-vg}}{i!} \tag{3.45}$$

where i=0, 1, 2, ...

For a given i, the total vehicle arrivals (N) is the i vehicles plus the one which triggers the phase, i.e.,

$$N = i + 1 \tag{3.46}$$

The expected N across i is

$$N = \sum_{i=0}^{\infty} \frac{(vg)^i e^{-vg}}{i!} (i + 1)$$

$$= vg + 1 \tag{3.47}$$

Since there is only one vehicle stopped, regardless of how many vehicles arrive in the green time, the expected number of vehicles stopped (N_{stop}) across i is

$$N_{stop} = \sum_{i=0}^{\infty} \frac{(vg)^i e^{-vg}}{i!} * 1$$

$$= 1 \tag{3.48}$$

Thus, the stop probability is

$$Ps = \frac{N_{stop}}{N}$$

$$= \frac{1}{vg + 1} \tag{3.49}$$

Equations (3.44) and (3.49) are used in the method as Equations (3.8) and (3.7), respectively.

CHAPTER FOUR
APPROXIMATION METHOD FOR PERFORMANCE EVALUATION OF SEMI-ACTUATED SIGNALS AT LOW VOLUMES

Introduction

The Analytical Method presented in the previous chapter provides a microscopic approach to estimate stop probabilities and average delays for semi-actuated signals when volumes are low. The method investigates various cycle patterns in terms of red and green times, and computes their probabilities. Also, stop probability and average delay of each cycle pattern are estimated. As discussed previously, however, applying the method would be complicated for signals with more than three phases or with special control capabilities, such as permissive periods. Because of this disadvantage, a second method is considered using a macroscopic approach.

Unlike the Analytical Method, which uses the individual red and green times, the method in this chapter uses average red and green times in the stop probability and in the average delay equations developed in the Analytical Method. Since this method does not analyze the various situations of individual cycles, it should be easier to apply where conditions are unfavorable to the Analytical Method. This second method will be referred to as the Approximation Method, in contrast to the first Analytical Method.

Because the Approximation Method uses average times, there is no need to consider individual cycles and their probabilities, which is generally complicated when conducted under the Analytical Method.

However, since the average times must be supplied to the method, they have to be either collected in the field or generated by a simulation model. In other words, the ease with which the Approximation Method is applied is at the expense of collecting additional data.

This chapter first addresses the concept of the Approximation Method, and develops the method. Then the method is validated against both the Analytical Method and the microscopic simulation model developed previously. Finally, the summary and discussions are presented.

Concept of the Method

As reviewed in Chapter Two, HCM, SOAP, and TRANSYT use average cycle lengths in models for pretimed signals to estimate average delays for actuated signals. This method produces reasonable approximations where traffic volumes are moderate to high. When traffic volumes are low, however, caution must be taken in using this method. As demonstrated earlier, this method could produce good approximations for semi-actuated signals where traffic volumes approach 300 vph. When traffic volumes are lower than 300 vph, however, the estimates are no longer reliable. The reason has been identified as phase skipping and dwelling. When traffic volumes approach 300 vph, phase skipping and dwelling rarely occur. The semi-actuated signals will functionally act like pretimed signals except that the phase lengths may vary from cycle to cycle. Hence, using the average times in models for pretimed phases should produce reasonable approximations. However, when traffic volumes are much lower than 300 vph, phase skipping and dwelling occur frequently. Models for pretimed phases are no longer valid for actuated phases, since they don't take phase skipping and dwelling into account.

The above findings suggest two points: (1) stop probability and average delay equations for pretimed phases cannot be directly applied to actuated phases when traffic volumes are low, and (2) using average times to substitute individual times could work under low volumes if equations consider phase skipping and dwelling. Since the equations developed in the Analytical Method have considered phase skipping and dwelling, it would be a reasonable approach to use average red and green times in these equations. The development of such a method is the subject of this chapter.

Method Development

Since the approach of this method is to apply the average values in the equations developed in the Analytical Method, the intuitive way to do this is to determine the average values, then to substitute them into the equations. However, actuated phases cause problems, both in applying the equations and in determining the averages, since there are two sets of equations, one for the case of a zero effective red time, and the other for an effective red time greater than zero. In the following, the problems will be explained and the treatments will be discussed. The non-actuated phase will be treated first.

The Non-Actuated Phase

Since the non-actuated phase will not be skipped regardless of whether it has traffic demand or not, it generally acts like a pretimed phase, except that its red and green lengths may vary from cycle to cycle. Because there is no phase skipping, the average red and green times can be easily determined by simply taking the averages of all the red and green times of individual cycles. Then they are input into Equations (3.3) and (3.4) to calculate stop probability and average

delay. For convenience, Equations (3.3) and (3.4) are rewritten as functions of R and G, where R and G are average red and green times, respectively.

$$Ps = \frac{R + G_s}{R + G} \tag{4.1}$$

$$d = \frac{R}{2.6} Ps \tag{4.2}$$

$$\text{where } G_s = \frac{vR}{s - v} \tag{4.3}$$

Actuated Phases

Actuated phases may be skipped due to lack of traffic demand. When a phase is skipped, there is no vehicle arrival during the corresponding red time. Because of this, the Analytical Method uses effective red time (which subtracts the red time without arrivals from the actual red time) in Equations (3.5) and (3.6) to calculate stop probabilities and average delays for the actuated phases. To comply with this in the Approximation Method, the red time corresponding to a skipped phase is also excluded from the total red time in determining the average red time.

When dwell occurs, the actuated phase following the non-actuated phase terminates the dwell. Similarly to phase skipping, the actuated phase has no arrival until it is activated by a vehicle (which also terminates the dwell). Hence, the actuated phase has a zero effective red time in the cycle. In conclusion, when an actuated phase appears, its effective red time is normally positive, but is zero when the phase terminates the dwell.

Recall that in computing stop probabilities and average delays, Equations (3.5) and (3.6) are for a positive effective red time and Equations (3.7) and (3.8) are for a zero effective red time. Again, in accordance with this difference, in the Approximation Method, the green occurrences of an actuated phase are also split into two parts according to their effective red times.

The required logic is summarized in the flow chart shown in Figure 4.1 to determine the average parameters. The chart determines the total effective red time (TER), the number of green occurrences (Ng), and the green occurrences with a positive effective red time (Nr). In the figure, an accumulator called red increment is used to accumulate the red time. When the phase is skipped, the red increment is reset to zero and the procedure goes to the next cycle. When the phase appears, Ng is increased by one. When dwell occurs, and is terminated by the phase, the red increment is reset to zero again. Otherwise, the red increment is added to TER, and Nr is increased by one.

After TER, Ng, and Nr are obtained, the other parameters can be computed in the following way:

$$R = TER/Nr \tag{4.4}$$

$$Nd = Ng - Nr \tag{4.5}$$

$$Ns = Nc - Ng \tag{4.6}$$

where Nd = green occurrences with a zero effective red time,

Ns = times of the phase being skipped, and

Nc = the total number of cycles.

It should be noted that there is no need to determine the average green time (G) since its value will be the same as the initial green

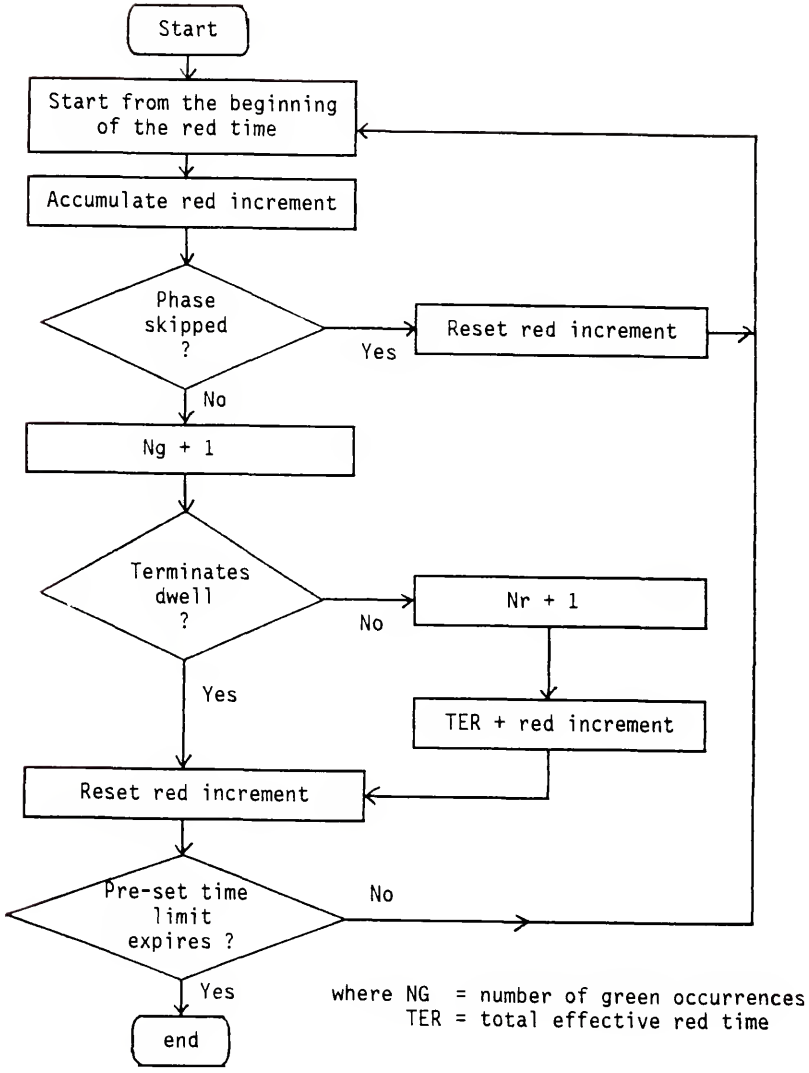


Figure 4.1. Determining the Total Effective Red Time and the Number of Green Occurrences.

time (g). This is because that the actuated phases are assumed to terminate the green times after the initial green time completes.

After the parameters are obtained, the next task is to input them into the equations. The task is easier where dwell does not happen. In this situation, Equations (3.5) and (3.6) are first changed to the following forms:

$$Ps = e^{-vR} + (1 - e^{-vR}) \frac{R + G_s}{R + G} \tag{4.7}$$

$$d = \frac{R^2}{2(R + G)} + e^{-vR} \frac{G(G + 2R)}{2(R + G)} + (1 - e^{-vR}) \frac{G_s^2}{2(R + G)} \tag{4.8}$$

Since e^{-vR} is the probability of no vehicle arriving in the time interval of R, it can be regarded as the probability of the phase being skipped. Since the phase is skipped Ns times out of Nc cycles, the percentage of phase skipping is Ns/Nc. Hence, e^{-vR} can be replaced by Ns/Nc. Similarly, $(1 - e^{-vR})$ can be regarded as the probability of the phase not being skipped, and can thus be replaced by Ng/Nc. As a result, Equations (4.7) and (4.8) can be changed to

$$Ps = \frac{Ns}{Nc} + \frac{Ng}{Nc} \frac{R + G_s}{R + G} \tag{4.9}$$

$$d = \frac{R^2}{2(R + G)} + \frac{Ns}{Nc} \frac{G(G + 2R)}{2(R + G)} + \frac{Ng}{Nc} \frac{G_s^2}{2(R + G)} \tag{4.10}$$

The estimation procedure ends at this point if dwell does not happen, i.e., Nd = 0. If on the other hand Nd is greater than zero, more computations are required. Since green occurrences (Ng) have been split into Nr (positive effective red time) and Nd (zero effective red time), the computations are also split accordingly.

For positive effective red time, the total vehicle arrivals (N) in a cycle can be estimated by multiplying the average arrival rate and the sum of the red and green times, i.e., $v(R + G)$. The number of vehicles stopped (N_{stop}) in one cycle can also be estimated by multiplying the stop probability and the total arrivals, i.e.,

$$N_{stop} = v(R + G)Ps$$

$$= v(R + G)\left[\frac{Ns}{Nc} + \frac{Ng}{Nc}\,\frac{R + G_s}{R + G}\right] \tag{4.11}$$

Because positive effective red time occurs Nr times out of Ng green occurrences, the total N_{stop} and the total N in the Nr cycles are

$$N_{stop} = Nr\ v(R + G)\left[\frac{Ns}{Nc} + \frac{Ng}{Nc}\,\frac{R + G_s}{R + G}\right] \tag{4.12}$$

$$N = Nr\ v(R + G) \tag{4.13}$$

On the other hand, for zero effective red time $N_{stop} = 1$, since the only vehicle stopped in one cycle is the one which activates the actuated phase. In addition, the total arrivals in this case can be estimated by multiplying the average arrival rate and the average green time, i.e.,

$$N = vG \tag{4.14}$$

Because zero effective red time occurs Nd times out of Ng green occurrences, the total N_{stop} and the total N in the Nd cycles are

$$N_{stop} = Nd \tag{4.15}$$

$$N = Nd * vG \tag{4.16}$$

Combining (4.12) and (4.15), the total N_{stop} in the Ng green occurrences is

$$N_{stop} = Nr\ v(R + G)\left[\frac{Ns}{Nc} + \frac{Ng}{Nc}\,\frac{R + G_s}{R + G}\right] + Nd \tag{4.17}$$

Combining (4.13) and (4.16), the total N in the Ng green occurrences is

$$N = Nr\ v(R + G) + Nd * vG \tag{4.18}$$

The stop probability therefore is

$$Ps = \frac{N_{stop}}{N}$$

$$= \frac{Nr\ v(R + G)\left[\frac{Ns}{Nc} + \frac{Ng}{Nc}\,\frac{R + G_s}{R + G}\right] + Nd}{Nr\ v(R + G) + Nd * vG} \tag{4.19}$$

The computations of average delay follow the same logic. For positive effective red time, the total delay in one cycle can be estimated by multiplying the average delay per vehicle and the total arrivals, i.e.,

$$D = v(R + G)d$$

$$= v(R + G)\left[\frac{R^2}{2(R + G)} + \frac{Ns}{Nc}\,\frac{G(G + 2R)}{2(R + G)} + \frac{Ng}{Nc}\,\frac{G_s^2}{2(R + G)}\right] \tag{4.20}$$

Because positive effective red time occurs Nr times, the total delay in the Nr cycles is

$$D = Nr\ v(R + G)\left[\frac{R^2}{2(R + G)} + \frac{Ns}{Nc}\,\frac{G(G + 2R)}{2(R + G)} + \frac{Ng}{Nc}\,\frac{G_s^2}{2(R + G)}\right] \tag{4.21}$$

For zero effective red time, since the average delay is zero, there is no extra delay created. Therefore, Equation (4.21) is the total delay in the Ng green occurrences. To divide the total delay by the total arrivals, the average delay is

$$d = \frac{Nr\ v(R+G)\left[\frac{R^2}{2(R+G)} + \frac{Ns}{Nc}\,\frac{G(G+2R)}{2(R+G)} + \frac{Ng}{Nc}\,\frac{G_s^2}{2(R+G)}\right]}{Nr\ v(R+G) + Nd * vG} \qquad (4.22)$$

For clarity, the above equations and the conditions for their use are summarized in Figure 4.2. Equations (4.1) and (4.2) are for the non-actuated phase. Equations (4.9) and (4.10) are for the actuated phase where there is no green occurrence with zero effective red time. Otherwise, Equations (4.19) and (4.22) should be used.

Tests of the Approximation Method

The Approximation Method was tested against both the Analytical Method and the simulation model developed previously. The method was developed into a computer program called DELVACS, which is an acronym for Delay Estimation for Low Volume Arterial Control Systems. The DELVACS program will be described in more detail in the next chapter. Briefly speaking, the program allows the user the choice of entering the volumes alone, or of entering both the volumes and the computational parameters (such as the average red and green times). When computational parameters are not entered, they will be generated by the program, using simulation. Then the computational parameters are input to the equations in Figure 4.2 to arrive at stop probabilities and average delays.

A three-phase signal under both isolated and coordinated controls was tested using the DELVACS program. The only inputs supplied were the volumes, and the computational parameters were generated by the program. As in the test of the Analytical Method, 216 sets of volumes were tested for both controls—the three phases were given volumes from 50 vph to

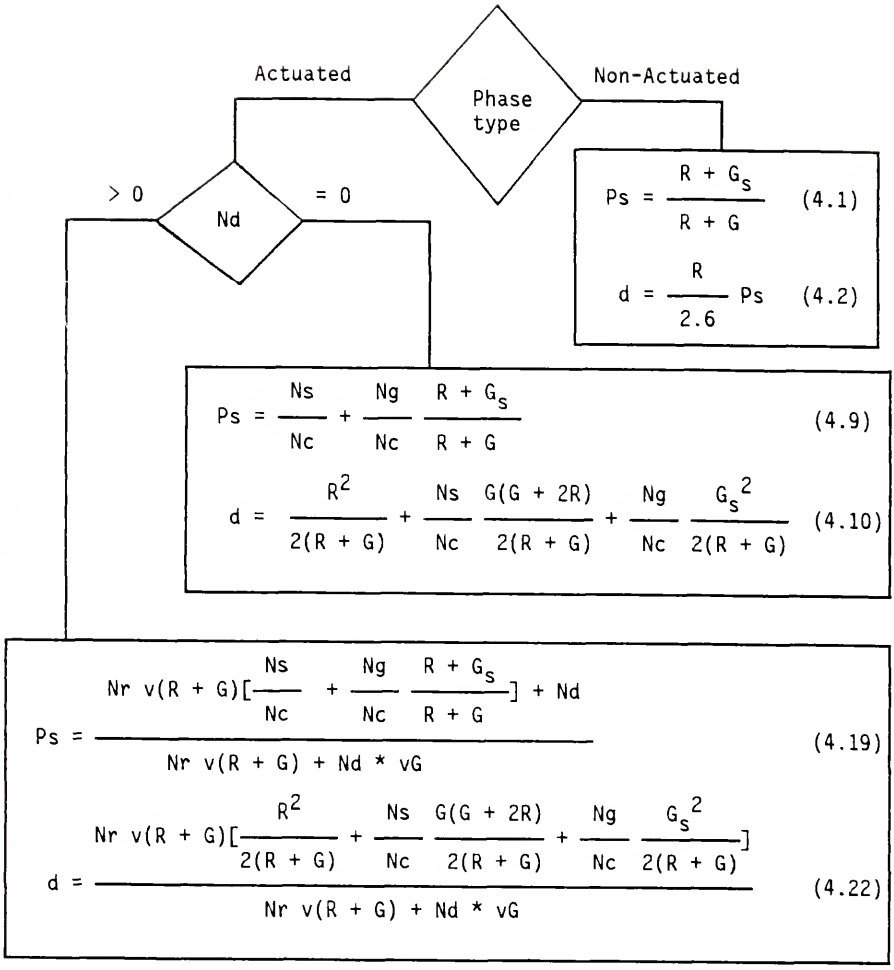


Figure 4.2. Stop Probability and Average Delay Equations and the Conditions for Their Use under the Approximation Method.

300 vph with 50 vph increments. Each set of volumes was tested for 6,000 seconds.

Comparison with Simulation

Part of the results are shown in Figure 4.3, which presents four comparisons: stop probabilities and average delays of phase 2 under both isolated and coordinated controls when phase 3's volume is 50 vph. Since other sets of results show the same pattern, they are omitted.

The stop probabilities and average delays from the simulation model shown in Figure 3.6 are duplicated in this figure. An inspection suggests that the results from the Approximation Method and simulation follow the same pattern. For average delay, about half of the data points from the Approximation Method fall within one standard deviation of the mean from the simulation model. For stop probability, the data points from the two methods adhere very closely when the signal is under coordinated control. When the signal is under isolated control, the data points still follow the same pattern, but with much more dispersion.

Comparing Figures 3.6 and 4.3, the Analytical Method agrees more closely to the simulation model than the Approximation Method does. This suggests that the Analytical Method is a better predictor than the Approximation Method. However, considering the relative ease with which the stop probabilities and average delays may be determined in the Approximation Method, it is reasonable to conclude that it could be used as a cost-effective substitute for the Analytical Method for the purposes of stop probability and average delay estimation.

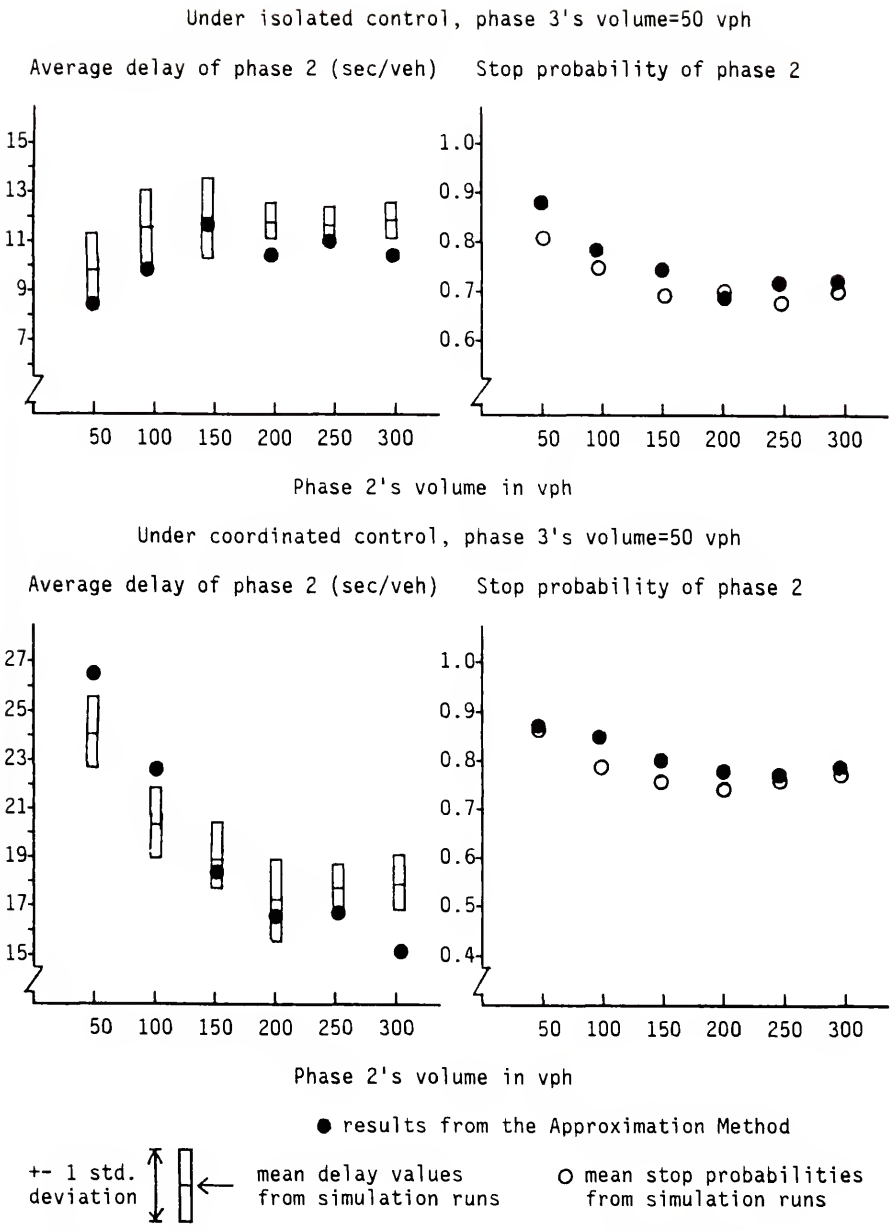


Figure 4.3. Stop Probability and Average Delay Comparisons, the Approximation Method vs. Simulation.

Comparison with the Analytical Method

Results from both the Analytical and Approximation Methods are compared in Figure 4.4 to illustrate their differences. Again, the comparison shows only the stop probabilities and average delays of phase 2 under both isolated and coordinated controls when phase 3's volume is 50 vph. In this figure, the stop probabilities from the two methods agree closely. For average delay, the results are also close when the signal is under coordinated control, but there is more dispersion under isolated control. In most cases, however, the differences are within two seconds per vehicle.

Summary and Discussions

Since the Analytical Method would be complicated to apply where signals have more than three phases, or have special control capabilities, the Approximation Method is proposed in this chapter. This method does not analyze the various situations of individual cycles, instead, it uses average values in equations adopted from the Analytical Method. Because of this, this method should be easier to apply where conditions are unfavorable to the Analytical Method.

Besides traffic volumes, the applications of the Approximation Method require collecting additional data (such as the average red and green times), which can be measured in the field or generated by simulation. In contrast, the Analytical Method requires the signal settings only (such as the background cycle length and the minimum green intervals). The settings can be obtained from either the signal controller or the agency. Also, the comparisons of these two methods show that the Analytical Method is a better predictor than the Approximation Method. However, considering the greater ease with which

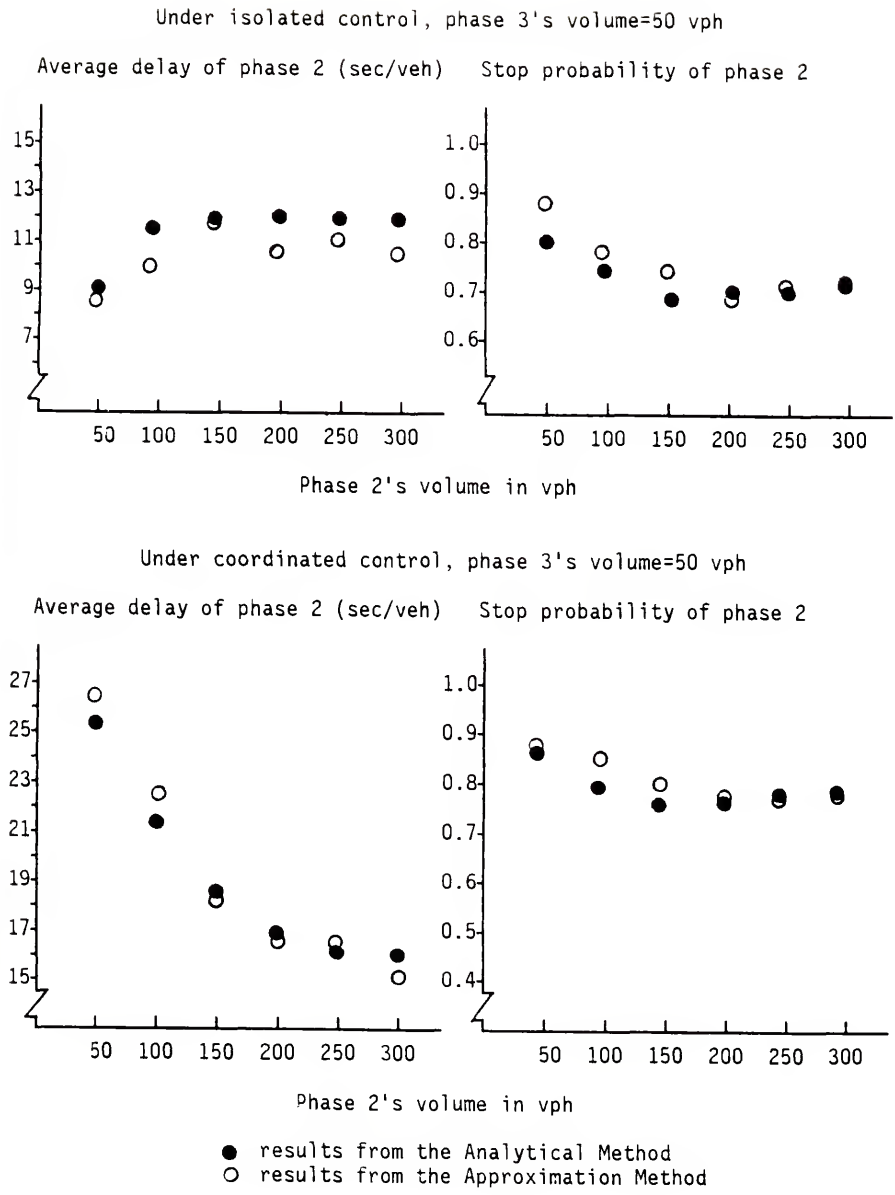


Figure 4.4. Stop Probability and Average Delay Comparisons, the Approximation Method vs. the Analytical Method.

the Approximation Method is applied, it could be concluded that the Approximation Method offers a cost-effective substitute for the Analytical Method in estimating stop probabilities and average delays.

The Approximation Method has been developed into the DELVACS program. The next chapter will present an application using the DELVACS program to dynamically determine the need to interconnect or release signal coordination on an arterial roadway.

CHAPTER FIVE
DECISION BETWEEN COORDINATION AND FREE OPERATIONS

Introduction

This chapter develops a method to help traffic engineers make a choice between coordination and free operations on arterial roadways, controlled by pretimed or semi-actuated signals with light traffic on cross streets. A performance index (PI), which is a linear combination of vehicular delay and number of stops, is used in the method to quantify the costs under both operations. From the standpoint of system performance, a lower PI value indicates a better operation. This method is referred to as the decision making process in the remainder of this chapter.

The decision making process has been implemented as a computer program called DELVACS (Delay Estimation for Low Volume Arterial Control Systems). DELVACS is already capable of dealing with semi-actuated signals, but it is currently being modified under the sponsored project associated with this research to handle both pretimed and semi-actuated signals. DELVACS will also be incorporated into the AAP (Arterial Analysis Package) [3] to allow the user to run the AAP and DELVACS together, using a common data set.

A hypothetical artery controlled by four semi-actuated signals in close proximity can be used to demonstrate the decision making process using DELVACS. The four signals are designed to represent various signal operations, including two-phase and three-phase, and with and

without permissive periods. Two cases are investigated in the example, with coordination better in one case and isolated operation in the other.

The implementation of the decision making process on personal-computer-based (PC-Based) signal control systems requires some further consideration. As reviewed in Chapter Two, PC-Based signal systems have three levels of control: signal controllers, on-street masters, and the central computer. The decision making process can be implemented on either on-street masters or the central computer. Both implementations have advantages and disadvantages, which are explored, and the problems as well as their resolutions are discussed.

This chapter is divided into four sections according to the previously stated objectives. The first section presents the decision making process. The second section describes the DELVACS program. The third illustrates the use of the decision making process by a hypothetical example. Last is the discussion of the implementation of the decision making process on PC-Based signal control systems.

Decision Making Process

The purpose of this process is to make a choice between coordination and free operations on arterial roadways when traffic is light during off-peak hours. The decision is based on system performance in terms of the PI. For given traffic conditions, the PIs of both coordination and free operations are computed and compared in order to decide which operation is more efficient.

The process consists of two major components: estimating stop probabilities and average delays, and computing PIs. Stop probabilities and average delays are estimated on an intersection by intersection

basis. Either of the two previously presented methods, Analytical or Approximation, can be used for the estimation purpose for semi-actuated signals. The PI combines delays and number of stops within the system. The process is divided into four steps as illustrated in Figure 5.1: determine progression factors (PF), compute stop probabilities and average delays at each intersection under each control, compute the PI value under each control, and compare the two PIs to make the decision.

Step 1 determines PF values at each intersection. The PF values will be used in Step 3 to adjust delays and number of stops to account for the influence of traffic progression when signals are coordinated. The 1985 Highway Capacity Manual (HCM) [19] Table 9-13 provides the PF threshold values based on degree of saturation and arrival type. The degrees of saturation in this table have three threshold values which are 0.6, 0.8, and 1.0. The selection of 0.6 degree of saturation would satisfy most cases under low volume conditions.

Arrival type, as reviewed in Chapter Two, can be assessed by the platoon ratio using Equation (2.1) or by the band ratio using Equation (2.2). It should be remembered that using the platoon ratio to assess arrival type requires field observations, while using the band ratio does not.

From the HCM's Table 9-13, it can be seen that for semi-actuated signals, only arterial through and right-turning movements are affected by traffic progression. Others, including the arterial left-turning movements, are not. This principle is used in the decision making process.

Step 2 estimates stop probability and average delay for each movement at each intersection. For pretimed signals, Webster and

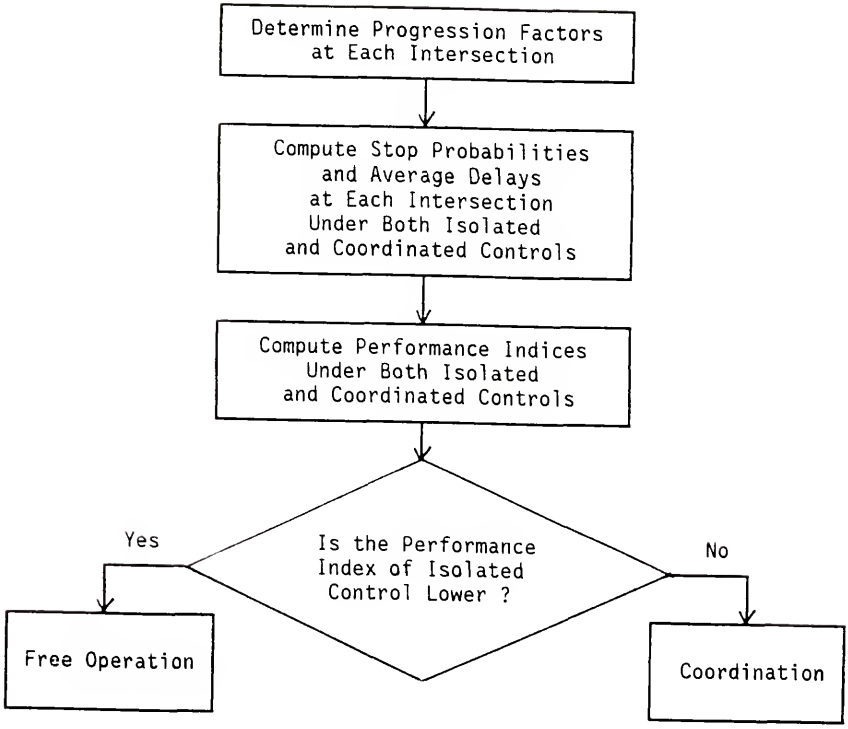


Figure 5.1. Block Diagram of the Decision Making Process.

Cobbe's [57] stop probability and average delay equations can be used for this purpose. For semi-actuated signals, the Analytical Method or the Approximation Method can be used.

Step 3 computes the system PI for each control. The system PI is a weighted sum of number of stops and total delay across movements, phases, and intersections. The number of stops is computed by multiplying the stop probability and the flow rate. The total delay is computed by multiplying the average delay and the flow rate. The PI in the form of a linear combination of total delay and number of stops has been extensively used in many signal design and evaluation tools, such as SOAP [52] and TRANSYT-7F [56].

$$PI = \sum_{i=1}^{n} \sum_{j=1}^{m_i} \sum_{k=1}^{o_{ij}} PF_{ijk} \, (D_{ijk} + w * s_{ijk}) \qquad (5.1)$$

where PI = system performance index;

n = number of signals on the artery;

m_i = number of phases at intersection i;

o_{ij} = number of movements in phase j at intersection i;

PF_{ijk} = progression factors for movement k in phase j at intersection i;

D_{ijk} = total delay in vehicle-seconds for movement k in phase j at intersection i;

s_{ijk} = number of stops in one hour for movement k in phase j at intersection i; and

w = stop penalty.

The stop penalty establishes the weighting relationship between delay and stop. Similarly to SOAP, a factor of 30 is used as the default value in the DELVACS program.

Finally in step 4 is to compare the two system PIs. A lower system PI value indicates that its associated operation costs less, and thus is more desirable.

The DELVACS Program

The decision making process was implemented as the DELVACS program, in which the Approximation Method is used to calculate stop probabilities and average delays for semi-actuated signals. This section introduces the program's basic functions, input requirements, and outputs.

Basic Functions

Remember that in the Approximation Method, both the traffic flow rates and signal operational parameters must be supplied. The signal operational parameters can either be observed in the field or generated by simulation. A simulation capability was built into DELVACS to generate signal operational parameters based on input traffic flow rates. In other words, DELVACS allows the user the choice of inputting the flow rates alone, or of inputting both the flow rates and signal operational parameters. An overview of the program is illustrated in the flow chart shown in Figure 5.2. The program contains three major modules

. Data Input Manager;

. Simulator; and

. Evaluator.

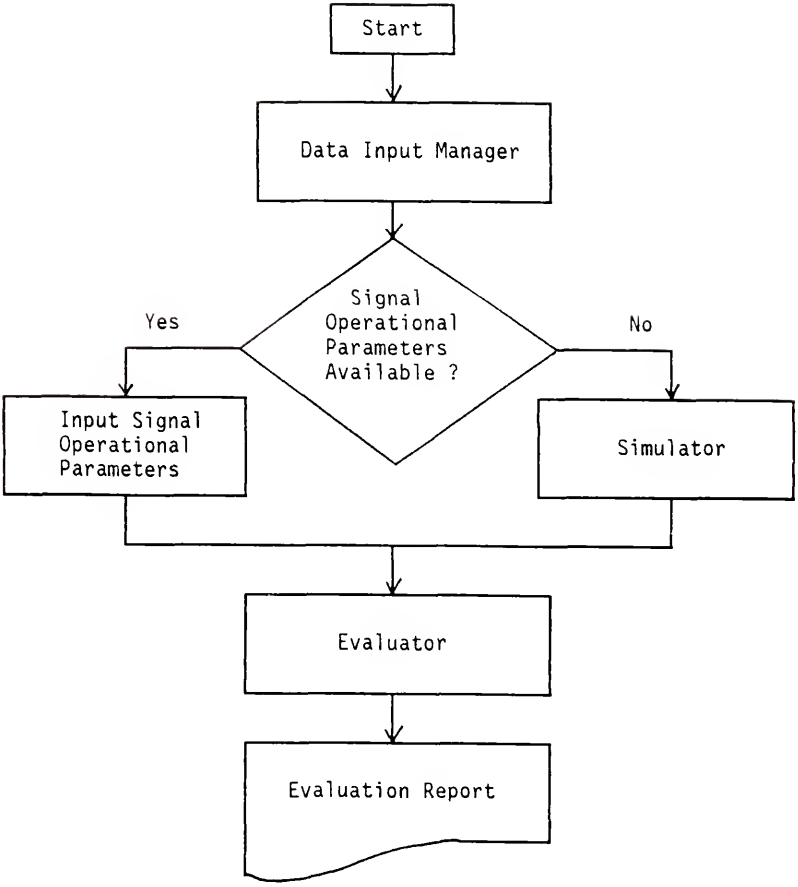


Figure 5.2. Flow Chart of the DELVACS Program.

The Data Input Manager (DIM) is designed to simplify data input through interactive menus. Currently, the DIM is simply a screen to allow the user to input data, but it will be incorporated with the AAPDIM (Arterial Analysis Package Data Input Manager) to conform to the AAP coding requirements. This will allow the user to run the AAP and DELVACS together, using a common data set.

The Simulator simulates semi-actuated signals' operations to generate the signal operational parameters. The inputs of the Simulator include traffic flow rates and signal settings. The Evaluator calculates the performance of individual intersections and the artery as a whole using the Approximation Method. Then the performances of coordination and free operations are compared to decide which one is more efficient.

Input Requirements

Two kinds of data are required, depending on whether simulation is requested or not. Basic data must be supplied in all cases, but signal operational parameters are required only when simulation is not requested. Basic data can further be categorized into three levels. Level one is artery-wide global information, which remains constant across all intersections within the artery. Level one data include

- w, the stop penalty with a default value of 30;
- s, the saturation flow rate in vehicles per hour with a default value of 1800 vph;
- artery name; and
- number of intersections.

Level two is intersection data which reflect particular characteristics of a given intersection. Level two data contain

. cross street name;

. number of non-actuated phases; and

. number of actuated phases.

Level three is concerned with phases and movements and includes

. V, the average flow rate in vehicles per hour;

. PF, the progression factor;

. G_{min}, the minimum seconds of green time for non-actuated phase; and

. g, the initial seconds of green time for actuated phase.

Signal operational parameters have only one item in level two, which is signal control features, such as permissive periods. Chapter Four gives a detailed definition of the items in level three, which are as follows:

. Nc, the number of cycles;

. G, the average seconds of green time;

. R, the average effective red time;

. Ng, the number of green occurrences; and

. Nd, the number of green occurrences with a zero effective red time.

Program Outputs

DELVACS produces four types of outputs according to the user's need.

. Summary of input data—this allows the user to scan the input to ensure that all items were entered correctly.

. Individual intersection performance—this include the stop probability, average delay, degree of saturation, total delay, number of stops, and performance index value.

- Artery performance—this report contains the total number of stops, total delay, and performance index value of the artery as a whole.
- Intermediate outputs of the Simulator—two intermediate tables providing the internal information generated by the Simulator are available. The first depicts the starting and ending times of each phase, cycle by cycle. The phase sequence and phase lengths in each cycle can be easily identified. The second table provides the operational parameters derived from the times in the first table.

Case Studies

Decision on an Artery

The objective of this presentation is to illustrate the decision making process using the DELVACS. As illustrated in Figure 5.3, this example uses a hypothetical north-south artery with four intersections, all controlled by semi-actuated signals. The signal phasing sequences and the input data to the DELVACS (with simulation requested) are also shown in this figure. The signal at intersection 1 has two phases, and others have three. Phase 1 of the four signals controls the arterial through movements in non-actuated mode. Phases 2 and 3 operate in actuated mode to control arterial left turns and cross street traffic. Permissive periods are used at intersections 3 and 4, but not at intersections 1 and 2. This arrangement was intended to illustrate various situations in the example.

The progression adjustment method in the HCM is used in this example to account for progression. When signals run freely, random flows are assumed on both the artery and cross streets. Thus, the PF

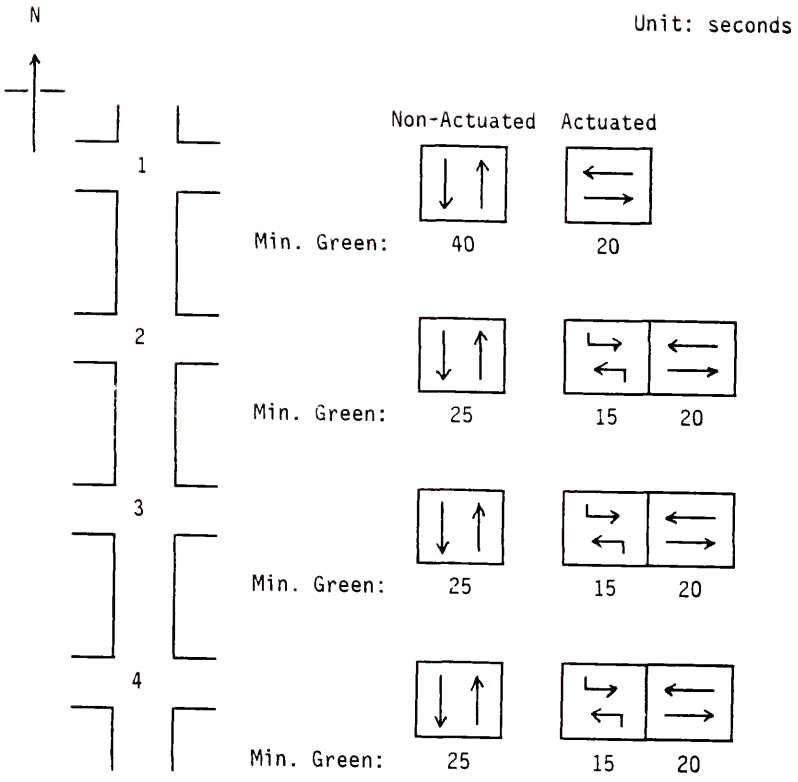


Figure 5.3. Artery Layout, Phase Sequences, and Timing Settings of the Example.

value of 1.00 is used for all movements. When signals are coordinated, the arrival type of four is assumed for both northbound and southbound through movements, and other movements are assumed to be random. (Arrival type four, a moderate progression quality, is arbitrarily chosen as a conservative example.) From the HCM's Table 9-13, the PF value of 0.72 is used for northbound and southbound through movements. However, the southbound through at intersection 1 and the northbound through at intersection 4 are still assumed to be random, since they are entry flows.

Two cases are investigated in this example. The traffic flow rates of the two cases are presented in Figure 5.4. Case 1 has lighter traffic flows both on the artery and cross streets. The stop probabilities, average delays, and PIs produced from the DELVACS for the two types of operations in each of the two cases are summarized in Tables 5.1 through 5.4. Tables 5.1 and 5.2 respectively show case 1 under coordinated and isolated control, and Tables 5.3 and 5.4 are analogous for case 2.

One observation stands out clearly when comparing Tables 5.1 and 5.2 (case 1), or Tables 5.3 and 5.4 (case 2). The PI values of the non-actuated phases under coordinated operation are always lower than those under free operation. In contrast, the PI values of the actuated phases under coordinated operation are higher than those under free operation. In fact, this observation is consistent with the general belief that coordination reduces delays and stops of the major street traffic at the expense of extra delay and stops to the cross street traffic.

The system PIs for the two cases, under both types of control, are shown in Table 5.5. In case 1, coordinated operation has a higher

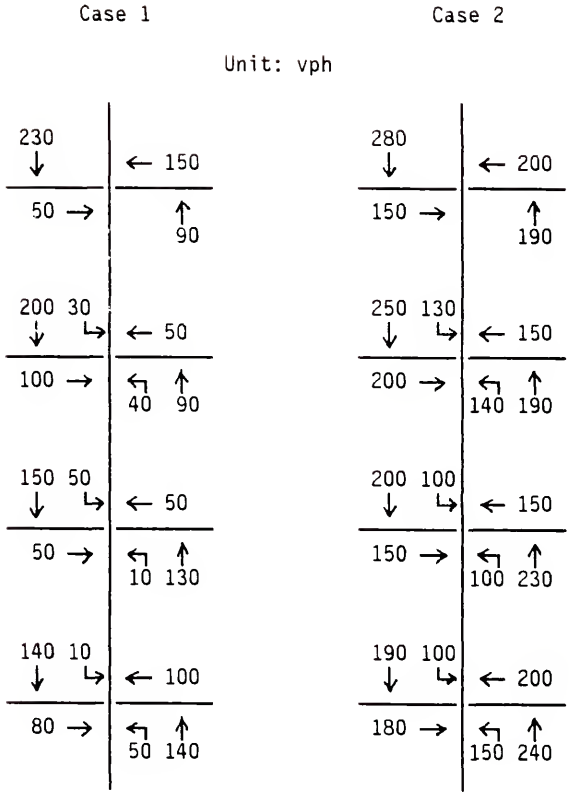


Figure 5.4. Traffic Flow Rates in Cases 1 and 2 of the Example.

Table 5.1. Measures of Effectiveness and Performance Indices Under Coordinated Control in Case 1.

Intersection	Phase and movement	Phase 1		Phase 2				Intersection PI
		NB TH	SB TH	EB TH	WB TH			
1	Volume (vph)	90	230	50	150			11910
	Stop prob.	0.28	0.3	0.77	0.81			
	Average delay	2.13	2.32	19.05	19.14			
	PF	0.72	1.00	1.00	1.00			
	PI	682	2604	2108	6516			
Intersection	Phase and movement	Phase 1		Phase 2		Phase 3		Intersection PI
		NB TH	SB TH	NB LT	SB LT	EB TH	WB TH	
2	Volume (vph)	90	200	40	30	100	50	14045
	Stop prob.	0.34	0.36	0.92	0.91	0.84	0.82	
	Average delay	3.08	3.28	28.86	28.85	23.10	23.06	
	PF	0.72	0.72	1.00	1.00	1.00	1.00	
	PI	861	2028	2258	1685	4830	2383	
3	Volume (vph)	130	150	10	50	50	50	10869
	Stop prob.	0.33	0.33	0.88	0.89	0.89	0.89	
	Average delay	3.03	3.06	26.35	26.35	24.07	24.07	
	PF	0.72	0.72	1.00	1.00	1.00	1.00	
	PI	1210	1400	528	2653	2539	2539	
4	Volume (vph)	140	140	50	10	80	100	15155
	Stop prob.	0.42	0.42	0.88	0.87	0.82	0.82	
	Average delay	3.98	3.98	25.27	25.26	20.09	20.30	
	PF	1.00	0.72	1.00	1.00	1.00	1.00	
	PI	2321	1671	2584	514	3575	4490	

Table 5.2. Measures of Effectiveness and Performance Indices Under Isolated Control in Case 1.

Intersection	Phase and movement	Phase 1		Phase 2				Intersection PI
		NB TH	SB TH	EB TH	WB TH			
1	Volume (vph)	90	230	50	150			10854
	Stop prob.	0.31	0.34	0.78	0.76			
	Average delay	2.38	2.59	9.53	11.96			
	PF	1.00	1.00	1.00	1.00			
	PI	1051	2942	1647	5214			
Intersection	Phase and movement	Phase 1		Phase 2		Phase 3		Intersection PI
		NB TH	SB TH	NB LT	SB LT	EB TH	WB TH	
2	Volume (vph)	90	200	40	30	100	50	12820
	Stop prob.	0.41	0.44	0.92	0.92	0.80	0.83	
	Average delay	3.51	3.75	17.46	16.10	9.00	6.98	
	PF	1.00	1.00	1.00	1.00	1.00	1.00	
	PI	1423	3390	1802	1311	3300	1594	
3	Volume (vph)	130	150	10	50	50	50	9896
	Stop prob.	0.37	0.37	0.95	0.88	0.90	0.90	
	Average delay	2.93	2.97	5.10	11.80	10.16	10.16	
	PF	1.00	1.00	1.00	1.00	1.00	1.00	
	PI	1824	2110	336	1910	1858	1858	
4	Volume (vph)	140	140	50	10	80	100	14091
	Stop prob.	0.49	0.49	0.89	0.94	0.77	0.77	
	Average delay	4.61	4.61	15.74	8.12	11.11	11.53	
	PF	1.00	1.00	1.00	1.00	1.00	1.00	
	PI	2703	2703	2122	363	2737	3463	

Table 5.3. Measures of Effectiveness and Performance Indices Under Coordinated Control in Case 2.

Intersection	Phase and movement	Phase 1		Phase 2				Intersection PI
		NB TH	SB TH	EB TH	WB TH			
1	Volume (vph)	190	280	150	200			19448
	Stop prob.	0.33	0.35	0.77	0.79			
	Average delay	2.52	2.67	16.68	16.77			
	PF	0.72	1.00	1.00	1.00			
	PI	1699	3688	5967	8094			
Intersection	Phase and movement	Phase 1		Phase 2		Phase 3		Intersection PI
		NB TH	SB TH	NB LT	SB LT	EB TH	WB TH	
2	Volume (vph)	190	250	140	130	200	150	34206
	Stop prob.	0.56	0.59	0.85	0.85	0.79	0.77	
	Average delay	6.98	7.25	20.30	20.30	16.87	16.78	
	PF	0.72	0.72	1.00	1.00	1.00	1.00	
	PI	3253	4491	6412	5954	8114	5982	
3	Volume (vph)	230	200	100	100	150	150	28773
	Stop prob.	0.53	0.52	0.86	0.86	0.80	0.80	
	Average delay	5.78	5.67	22.05	22.05	17.83	17.83	
	PF	0.72	0.72	1.00	1.00	1.00	1.00	
	PI	3590	3063	4785	4785	6275	6275	
4	Volume (vph)	240	190	150	100	180	200	35375
	Stop prob.	0.61	0.59	0.85	0.83	0.76	0.77	
	Average delay	7.44	7.21	20.05	19.98	15.10	15.13	
	PF	1.00	0.72	1.00	1.00	1.00	1.00	
	PI	6178	3408	6833	4488	6822	7646	

Table 5.4. Measures of Effectiveness and Performance Indices Under Isolated Control in Case 2.

Intersection	Phase and movement	Phase 1		Phase 2				Intersection PI
		NB TH	SB TH	EB TH	WB TH			
1	Volume (vph)	190	280	150	200			19025
	Stop prob.	0.36	0.38	0.74	0.76			
	Average delay	2.75	2.92	12.88	13.09			
	PF	1.00	1.00	1.00	1.00			
	PI	2575	4010	5262	7178			
Intersection	Phase and movement	Phase 1		Phase 2		Phase 3		Intersection PI
		NB TH	SB TH	NB LT	SB LT	EB TH	WB TH	
2	Volume (vph)	190	250	140	130	200	150	35733
	Stop prob.	0.62	0.64	0.84	0.83	0.75	0.73	
	Average delay	7.34	7.62	17.90	17.88	13.52	13.43	
	PF	1.00	1.00	1.00	1.00	1.00	1.00	
	PI	4929	6705	6034	5561	7204	5300	
3	Volume (vph)	230	200	100	100	150	150	29829
	Stop prob.	0.58	0.57	0.85	0.85	0.76	0.76	
	Average delay	6.04	5.92	18.87	18.87	13.73	13.73	
	PF	1.00	1.00	1.00	1.00	1.00	1.00	
	PI	5391	4604	4437	4437	5480	5480	
4	Volume (vph)	240	190	150	100	180	200	35724
	Stop prob.	0.63	0.61	0.85	0.83	0.75	0.75	
	Average delay	7.44	7.21	18.48	18.33	13.36	13.40	
	PF	1.00	1.00	1.00	1.00	1.00	1.00	
	PI	6322	4847	6597	4323	6455	7180	

Table 5.5. Desirable Operations in the Two Cases of the Example.

(a) Case 1

Operation	Intersection PI				System PI
	1	2	3	4	
Coordination	11,910	14,045	10,869	15,155	51,979
Isolation	10,854	12,820	9,896	14,091	47,661
Recommended action : Release the signal coordination					

(b) Case 2

Operation	Intersection PI				System PI
	1	2	3	4	
Coordination	19,448	34,206	28,773	353751	117,802
Isolation	19,025	35,733	29,829	35,724	120,311
Recommended action : Coordinate the signals					

system PI, which suggests that free operation would be more efficient. On the other hand, coordinated operation is better in case 2, since it has a lower system PI.

Control Shifts and Switching Conditions

Switching conditions are the traffic conditions under which a control shift between coordination and free operations would be needed. Switching conditions, if simple to calculate, could help traffic engineers quickly determine the need to change the signal operation. Unfortunately, switching conditions are generally too involved to be developed. For example, in the above case study, since the traffic volume and the progression adjustment factor of each movement are factors of the final decision, it would be impossible to identify all the switching conditions. Thus, switching conditions can be established only in some very simple situations. The following illustrates the switching conditions at a single intersection, controlled by a two-phase semi-actuated signal.

The intersection layout, the signal phasing sequence, and the signal setting are shown in Figure 5.5. In this figure, phase 1 is non-actuated, and controls the eastbound major street traffic, while phase 2 is actuated, and controls the northbound cross street traffic. Under this arrangement, the decision between coordination and free operations is affected by three factors which are major street volume, cross street volume, and major street PF. (Cross street PF is always 1.00, under the assumption that the actuated phase is not influenced by traffic progression.) Since total volume and cross street portion of the total volume can substitute for the major street and cross street volumes, and since they are easier to explain the results, the three factors used for

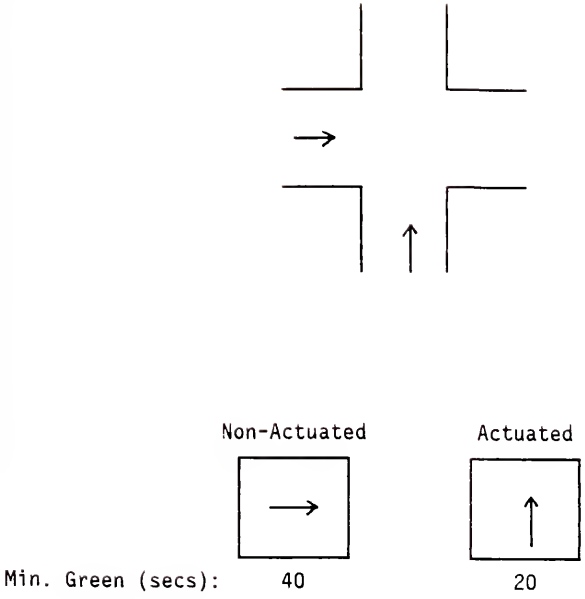


Figure 5.5. Intersection Layout, Phase Sequence, and Timing Setting of the Switching Condition Example.

the establishment of switching conditions are total volumes, cross street portions of total volume, and major street PF values.

The DELVACS with simulation was used for both isolated and coordinated controls. Under each kind of control, 162 sets of conditions were tested—the total volumes from 100 vph to 600 vph, with 100 vph increments, while the total volumes from 100 vph to 200 vph, with 25 vph increments; the percentages of cross street volume from 30% to 50%, with 10% increments; and the major street PF values under coordinated control from 0.50 to 1.00, with 0.10 increments. Each set of conditions was tested for 6,000 seconds.

The results are shown in Figure 5.6. In this figure, the x and y axes represent the major street PF values and the total volumes, respectively. The x-y plane is divided into two parts: upper left and lower right. In the upper left part, coordinated operation is better, while in the lower right part, isolated operation is better. The three curves which divide the x-y plane represent three cross street portions of total volume: 50%, 40%, and 30%.

This figure can be explained with basic knowledge. For a given total volume, coordination area falls in lower PF values, because when PF values are lower, the major street traffic would gain more benefit from coordination. On the other hand, when PF values are higher, the major street traffic would gain less benefit from coordination and the benefit may not offset the losses by cross street traffic due to coordination. Therefore, isolated operation would be better. When also considering the cross street portion of total volume, a higher percentage, say 50%, has a smaller coordination area requiring lower PF values. This is because when the total traffic is nearly equally

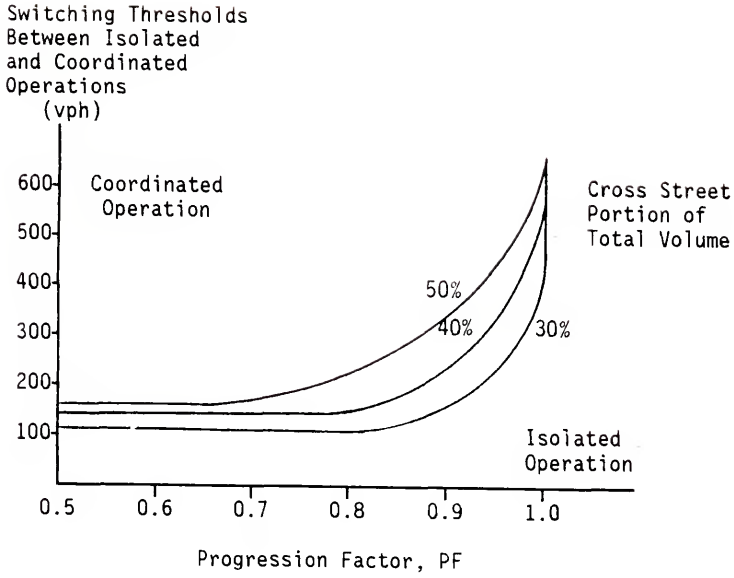


Figure 5.6. The Switching Thresholds of Total Intersection Volume for the Example Intersection with a Two-Phase Semi-Actuated Signal.

distributed on the two streets, the major street traffic would need a lower PF value in order to gain enough benefit from coordination to offset the greater losses by the cross street traffic. Conversely, when the percentage is lower, the cross street traffic is lighter compared to the major street traffic. Thus, the losses by the cross street traffic due to coordination can be more easily offset by the benefits gained on the major street traffic with a bigger PF value. The same rationale can be applied to explain the situation at a given PF value.

Application On PC-Based Signal Control Systems

The main purpose of this section is to explore the implementation of the decision making process on personal-computer-based (PC-Based) traffic signal control systems.

As reviewed regarding PC-Based signal systems in Chapter Two, the task of selecting signal plans is distributed to on-street masters, regardless of whether they are in time of day and day of week (TOD/DOW) mode or traffic responsive (TRSP) mode. On-street masters function on a stand-alone basis, primarily based on surveillance data gathered from sub-system detectors. The central computer functions as an editing and reporting station for overall monitoring. Close monitoring and interface with the on-street masters is not necessary, and the central computer can be turned off or used for other activities.

Under such an operational structure, the decision between coordination and free operations within one sub-system can be made at either the central computer or the on-street master, but both approaches have advantages and disadvantages.

To make the decision at the central computer, all the input data to run the DELVACS are passed from the sub-system to the central computer,

and an override command is then issued back to the on-street master from the central site, if the decision is made to change the current operation. The advantage of this approach is its easy implementation, as it requires no major changes on the system's hardware and software.

There are three major disadvantages to this approach. The first is increased user involvement, which is undesirable. This is because an operator at the central computer has to operate the process, overriding on-street masters' operations when needed. The second is that the process ceases when the central computer is turned off or used for other activities. The last disadvantage is an increased workload for both the communication lines and the central computer, because all the input data collected from sub-systems are sent to the central site, and all the computations are performed there. The increased workload on the communication lines and the central computer may disrupt the normal signal control operations.

The first problem of increasing user involvement can be resolved by developing a software to automatically process the DELVACS and interact with on-street masters. By designating the central computer as a master-control machine, which cannot be turned off or used for other activities, the second problem can be resolved. Executing the DELVACS on a separate personal-computer (or a main-frame computer, if available) can effectively minimize the disruption of the normal system operations and speed up the process.

The second approach of the implementation is to make the decision at on-street masters. This approach is efficient, but is more complicated to implement. By assigning this task to on-street masters, the functions of the central computer can remain simple, and thus the

spirit of PC-Based signal systems can be maintained. The operating cost can also be reduced because there is no need to transmit additional information between sub-systems and the central computer.

The major disadvantage of this approach is complexity, because the process has to be built into on-street masters by either software or hardware. The development of software requires close integration in the on-street master hardware environment, and the hardware modification rests on manufacturers' future system development.

Future hardware development could have two focuses: signal controllers and on-street masters. It would be desirable for the signal controller to conduct "field observation" by itself, recording the number of phase occurrences, accumulating green times, etc. In other words, the operational parameters could be collected from signal controllers. Doing so, there would be no need to run the simulation in the DELVACS, and the decision making process could be easily done on the on-street master by executing the Evaluator Module of the DELVACS program.

The placement of detectors is another consideration of the decision making process implementation. Detectors are placed on the road to collect traffic demand information, and are of two types: local detectors and system detectors. Local detectors gather traffic demand information solely for signal controller operation purpose, such as when to terminate the green light and whether to skip a phase. The data gathered by local detectors are not sent to on-street masters. Conversely, traffic information gathered by system detectors is passed to on-street masters for the operational purpose of the entire sub-system, such as selecting signal plans. These data can be temporarily

stored on on-street masters and then transmitted to the central computer for future use.

Since system detectors communicate with on-street masters, they are usually placed only at critical locations, to reduce operating cost. In other words, only the flow rates of the most important movements are fed into on-street masters. This brings up a problem in implementing the decision making process, since the flow rates of all movements are required in the performance computations, but only some of them can be obtained from the system detectors.

The decision making process could be performed by considering only the critical movements, in similar fashion to the TRSP mode selecting signal plans in response to traffic demand by using critical flow rates collected from system detectors. In other words, the PIs are calculated only for the critical movements, which are detected by system detectors, and the decision is made primarily based on the total performance of these movements.

The placement of system detectors may create another problem in the implementation of the decision making process. System detectors are usually placed at key locations, such as lanes with higher flow rates. This may result in a situation where all the system detectors are placed on the artery. In such a situation, with only arterial traffic evaluated, the decision making process cannot be applied, since the result may always indicate that coordinated operation is favored regardless of how low the arterial traffic flow rate is. The reason is clear, since coordination operation usually favors arterial traffic. Therefore, for the purpose of implementing the decision making process,

system detectors must be placed on both the artery and some cross streets.

Though detector placement is an important issue, it is too involved to be fully treated here, and it is somewhat tangential to the topic of this dissertation. This study therefore simply assumes that detectors were properly placed. In the next chapter, research is suggested to further investigate the topic of detector placement.

CHAPTER SIX
CONCLUSIONS AND RECOMMENDATIONS

This dissertation aims to develop a process for making the choice between coordination and free operations in response to traffic conditions, and to study the implementation of this process on personal-computer-based (PC-Based) signal control systems. The major steps accomplished in this research are summarized as follows:

1. Review the literature in the areas of signal performance evaluation, traffic progression models, techniques for making the decision between coordination and free operations, and PC-Based signal control system operations.
2. Develop two methods, the Analytical and Approximation Methods, for evaluating semi-actuated signals at low volumes, under both coordinated and free operations. The Analytical Method, based upon stochastic processes and probability theories, deals with microscopic cycles. The Approximation Method, on the other hand, is macroscopic, using average signal operational parameters instead of individual ones.
3. Propose the decision making process for deciding between coordination and free operations on arterial roadways with light traffic on cross streets, whether controlled by pretimed or semi-actuated signals. The decision is based on system operational performance in terms of total vehicular delay and number of stops.

4. Implement the decision making process as the DELVACS program, in which the Approximation Method is used to evaluate semi-actuated signals and the 1985 Highway Capacity Manual (HCM) progression adjustment method is used to account for traffic progression. A simulation capability is built into the DELVACS to generate signal operational parameters when they are not available.
5. Demonstrate the application of the decision making process using the DELVACS on a hypothetical artery, controlled by four semi-actuated signals in close proximity. Two cases with different flow rate combinations are investigated, with coordination better in one case and isolated operation in the other.
6. Explore the implementation of the decision making process on PC-Based signal control systems. The possible implementation approaches with advantages and disadvantages are discussed, and the resolutions to the potential problems are proposed.

Conclusions

The decision making process developed is able to help traffic engineers make more effective choices on light traffic signal control from the standpoint of system performance. The process can be used immediately on PC-Based signal systems. The conclusions listed below are offered as a result of this study.

1. The results of the literature review on signal performance evaluation indicate that very few models exist which deal exclusively with semi-actuated signal evaluation. A common evaluation practice, given this lack of appropriate models, is

the use of a model for pretimed signals with average data. However, this approach is not applicable when traffic is light, since phase skipping and dwelling are not considered.

2. The results of the literature review on traffic progression models indicate that the 1985 HCM provides an easy way to account for progression. When applying the method, arrival type can be assessed either by field observations or by computing the band ratio from time-space diagrams.
3. The direct analysis of semi-actuated signal operations is complicated because of stochastic characteristics. Thus stochastic processes and probability theory were applied to consider the various cycle patterns in the Analytical Method.
4. Under low volume conditions, actuated phases of semi-actuated signals can be assumed to terminate their green times after the initial green intervals elapse, since the probability of requiring green extensions is usually very small.
5. The phase sequence in one cycle of a semi-actuated signal is influenced only by that in the past cycle. Thus, the signal operations can be described by two consecutive cycles, and can be treated as a Markov chain.
6. Webster and Cobbe's stop probability and average delay equations for pretimed phases are not directly applicable for actuated phases under low volume conditions. The equations were modified to take phase skipping and dwelling into account.
7. When traffic volumes are low, the results from stop probability and average delay equations for actuated phases are

significantly different from the results of those for pretimed phases. However, when volumes are higher, they are close.

8. When the traffic volume of an actuated phase is very low, almost every vehicle will face a red light, and will be stopped (i.e., the stop probability approaches unity).
9. The performance indices of the non-actuated phases under coordinated operation are lower than those under free operation. In contrast, the performance indices of the actuated phases under coordinated operation are higher than those under free operation.
10. The Analytical Method is easy to apply when there are only two phases. But the computations would be too involved when signals have more than three phases, or have special control capabilities.
11. The Approximation Method is relatively easy to apply in most cases, but requires that extra data be either collected, or simulated.
12. The comparisons of the Analytical and Approximation Methods show that the Analytical Method is a better predictor for estimating stop probabilities and average delays, but the Approximation Method is cost-effective.
13. The application of the decision making process on PC-Based signal control systems can be implemented on either on-street masters or the central computer. Both implementations have advantages and disadvantages.
14. Implementing the decision making process on the central computer is easy to accomplish, but has three major

disadvantages: user involvement increases, the process ceases when the central computer is turned off or used for other activities, and the workload increases for both the communication lines and the central computer.

15. The three problems can be resolved by: developing a software to automatically process DELVACS and interact with on-street masters, designating the central computer as a master-control machine, and executing the DELVACS on a separate personal-computer or a main-frame computer.
16. Implementing the decision making process on on-street masters is efficient, since there is no need to transmit additional information between sub-systems and the central computer. But this approach is more complicated, since it primarily rests on manufacturers' future system development.
17. For the purpose of implementing the decision making process, system detectors must be placed on both the artery and some cross streets.
18. If the system detectors supply only certain critical movements data from the artery and cross street (both still being required), the decision making process could be accomplished by considering the performance of these movements.

Recommendations

Based on the limited situations investigated in this study, the two proposed signal evaluation methods produce reasonable performance estimations for semi-actuated signals under low volume conditions. Also, the decision making process provides a realistic means for making a choice between coordination and free operations. Logically, the next

step would be an empirical investigation to validate these methodologies and identify any needed adjustments.

In addition, several recommendations have emerged from this study, and fall into three areas: further improvements to the Analytical and Approximation Methods, enhancements to the DELVACS program, and further research warranted for the decision making process.

Several assumptions were made in the development of both the Analytical and Approximation Methods in order to simplify the analysis. The factors associated with these simplified assumptions would benefit from further consideration when dealing with real world situations. These factors include

1. Lost time—lost time was not considered in the two methods. Lost time is usually taken as a fixed number, such as 4 seconds per phase, in most analytical models to account for the total start-up delay, experienced by the first few vehicles in a standing queue when the signal turns to green, plus the non-use of the change interval. However, a smaller value for lost time should be used, since fewer vehicles and shorter cycles will be present in most cases under low volume conditions.
2. Yellow time—yellow time was not considered either. When considering yellow time, delay will be affected, particularly for actuated phases. For example, when the green light dwells on the non-actuated phase, the vehicle which activates the actuated phase following the non-actuated phase (which also terminates the dwell) will come to a stop and experience a delay of yellow time plus some lost time. Since lost and

yellow times were not considered in the methods, the vehicle was treated as stopped without any delay.

3. Moving queue—a vehicle joining a queue was assumed to be stopped, but this is not always the case. When the queue has started moving, the vehicle joining the end of the queue will only slow down and does not necessarily come to a stop. Therefore, the stop probability is overestimated in the two methods. However, the error is expected to be small, since the probability of joining a moving queue is proportional to the length of saturation green, but the saturation green time is usually very short under low volume conditions.

Moreover, these two methods use the 1985 HCM progression adjustment factors (PF) to account for the influence of traffic progression when signals are coordinated. It would be desirable to develop a self-contained model for estimating delays and stops under coordinated signal operations.

In its current status, the DELVACS program is fully operational, but with some limitations in applications. Three functional enhancements are suggested below.

1. The DELVACS is already capable of handling single ring operations without overlapping, but it would be desirable to expand the program's capabilities to deal with both dual ring and overlapping situations, since they are common operations in traffic actuated signals.
2. The saturation flow rate in the DELVACS defaults to 1800 vehicles per hour, which is the ideal value taken from the HCM. Since the HCM has provided a powerful technique for determining

saturation flow rate, it would be desirable to incorporate this technique into DELVACS to account for the various conditions that are not ideal.

3. The progression factor is an input to the DELVACS. Progression factors can be taken from the HCM's Table 9-13, provided arrival type is known. Arrival type can be assessed by platoon ratio with field observations or by band ratio using time-space diagrams. It would be desirable to incorporate the band ratio calculations using time-space diagrams into the DELVACS to eliminate the need for user-calculation. Certainly, a connection needs to be established with programs which are able to provide time-space diagrams. In fact, this would be one major reason to incorporate the DELVACS into the Arterial Analysis Package (AAP).

The choice between coordination and free operations can be made through the decision making process, but the outcome of this process depends partly on stop penalty, and the process relies on data provided from system detectors. Two research topics regarding such issues are suggested below.

1. Stop penalty—stop penalty plays a very important role in the decision making process, since it establishes the weighting relationship between delay and stop. Stop penalty values ranging from 20 to 50 have been shown to produce a good balance between stops and delay for average traffic conditions. But these values may not be applicable under low volume conditions, especially for actuated phases, because stop probabilities tend

to be higher. Further research could establish appropriate stop penalties under light traffic conditions.

2. The placement of system detectors—the decision making process relies on traffic information collected from detectors. Since only data from system detectors at critical locations are available, the decision needs to be made by considering only these critical movements, so the problem of where to place system detectors must be resolved. Although this problem is parallel to that involved with TRSP mode signal plan selection in UTC systems, the guidelines of detector placement provided for UTC Systems [46, 47] may not be directly applicable for the purpose of the decision making process. Additional research on this issue is therefore suggested.

BIBLIOGRAPHY

1. Akcelik, R. "Traffic Signals: Capacity and Timing Analysis," Australian Road Research Board, Research Report ARR No. 123, 1981.

2. Allsop, Richard E. "Delay at a Fixed Time Traffic Signal—I: Theoretical Analysis," Transportation Science, Vol. 6, pp.260-285, 1972.

3. "Arterial Analysis Package User's Manual," Report No. FHWA-IP-82-8, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1982.

4. Bullen, A. G. R., Hummon, N., Bryer, T., and Nekmat, R. "VIPAS: A Computer Model for the Optimal Design of a Vehicle Actuated Traffic Signal," presented at the 66th Annual Meeting of the Transportation Research Board, Washington, D.C., 1987.

5. Cayford, Randall "TRANSYT-7FC Enhanced TRANSYT Version for Actuated Signals, Programmers Guide," Institute of Transportation Studies, University of California at Berkeley, California, 1988.

6. Chang, E. C., Fambro, D. B., and Messer, C. J. "Effective of Quality of Traffic Signal Progression on Delay," Draft Final Report, Texas A & M University, College Station, Texas, 1988.

7. Chang, Edmond Chin-Ping "Developing Interconnection Guidelines for Isolated Traffic Signals," Transportation Research Record 1057, Transportation Research Board, Washington, D.C., pp.33-42, 1986.

8. Courage, Kenneth G., and Luh, John Z. "Computation of Signalized Intersection Service Volumes Using the 1985 Highway Capacity Manual," presented at the 67th Annual Meeting of the Transportation Research Board, Washington, D.C., 1988.

9. Courage, Kenneth G., and Thomas, Joseph M. "Microcomputer Applications in Traffic Control Systems," Proceedings of the 1983 Engineering Foundation Conference, San Diego, California, 1983.

10. Courage, Kenneth G., Wallace, Charles E., and Alqasem Rafig "Modeling the Effect of Traffic Signal Progression on Delay," presented at the 67th Annual Meeting of the Transportation Research Board, Washington, D.C., 1988.

11. Cowan, Richard "An Improved Model for Signalised Intersections with Vehicle-Actuated Control," Journal of Applied Probability, Vol. 15, pp.384-396, 1978.

12. de Laski, A. B., and Parsonson, P. S. "Traffic Detector Handbook," Report No. FHWA-IP-85-1, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1985.

13. "Evaluation of UTCS Control Strategies," Report No. FHWA-RD-76-150, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1976.

14. Gafarian, A. V., and Halati, A. "Statistical Analysis of Output Ratios in Traffic Simulation," presented at the 65th Annual Meeting of the Transportation Research Board, Washington, D.C., 1986.

15. Gartner, Nathan "OPAC: A Demand-Responsive Strategy for Traffic-Signal Control," Transportation Research Record 906, Transportation Research Board, Washington, D.C., pp.75-81, 1983.

16. Gerlough, Daniel L., and Huber, Matthew J. "Traffic Flow Theory," Transportation Research Board Special Report 165, National Research Conucil, Washington, D.C., 1975.

17. Hagen, Lawrence T., and Courage, Kenneth G. "A Comparison of Macroscopic Models for Signalized Intersection Analysis," presented at the 68th Annual Meeting of the Transportation Research Board, Washington, D.C., 1989.

18. "Handbook of Computer Models for Traffic Operations Analysis, Technical Appendix: Summary of Models and References," Report No. FHWA-TS-82-214, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1982.

19. "Highway Capacity Manual," Transportation Research Board Special Report 209, National Research Council, Washington, D.C., 1985.

20. Henry, R. D., Ferlis, R. A., and Kay, J. L. "Evaluation of UTCS Control Strategies—Executive Summary," Report No. FHWA-RD-76-149, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1976.

21. Hoel, Paul G., Port, Sidney C., and Stone, Charles J. "Introduction to Stochastic Processes," Houghton Mifflin Company, Boston, Massachusetts, 1972.

22. Hoshi, T. "Some Problems involving Delays at Traffic Intersections," Ph.D. Dissertation, John Hopkins University, Maryland, 1969.

23. Hunt, P. B. "The SCOOT On-Line Traffic signal Optimization Technique," International Conference On Road Traffic Signalling, Institute of Electrical Engineers, England, 1982.

24. Hurdle, V. F. "Signalized Intersection Delay Models—A Primer for the Uninitiated," Transportation Research Record 971, Transportation Research Board, Washington, D.C., pp.96-105, 1984.

25. Hutchinson, T. P. "Delay at a Fixed Time Traffic Signal—II: Numerical Comparisons of Some Theoretical Expressions," Transportation Science, Vol. 6, pp.286-305, 1972.

26. "Improved Operation of Urban Transportation Systems," Vol. 1, 2, and 3, Corporation of Metropolitan Toronta, Toronto, Canada, 1974, 1975, and 1976.

27. Kelman, Les "Workshop on Traffic Control for Small and Medium Sized Communities," Proceedings of the 1983 Engineering Foundation Conference, San Diego, California, 1983.

28. Lan, Joseph K. "The Future of Control In Small to Medium Communities," Proceedings of the 1983 Engineering Foundation Conference, San Diego, California, 1983.

29. Law, Averill M., and Kelton, W. David "Simulation Modeling and Analysis," McGraw-Hill Book Company, Highstown, New Jersey, 1982.

30. Lehoczky, J. P. "Variable Cycle Traffic Light," Ph.D. Dissertation, Stanford University, California, 1969.

31. Lieberman, E., Worrall, R. D., Wicks, D., and Woo J. "Traffic Network Analysis with NETSIM, A User's Guide," Report No. FHWA-IP-80-3, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1980.

32. Lin, Feng-Bor "Estimation of Average Phase Durations for Full-Actuated Signals," Transportation Research Record 881, Transportation Research Board, Washington, D.C., pp.65-72, 1982.

33. Lowrie, P. R. "The Sydney Coordinated Adaptive Traffic System—Principles, Methodology, Algorithms," Department of Main Roads, New South Wales, Australia, N.D.

34. Miller, A. J. "Settings for Fixed-Cycle Traffic Signals," Operations Research Quarterly, Vol. 14, 1963.

35. Newell, G. F. "Approximation Methods for Queues with Application to the Fixed-Cycle Traffic Light," S.I.A.M. Review, Vol. 7, pp.223-240, 1965.

36. Newell, G. F. "Properties of Vehicle-Actuated Signals: I. One-Way Streets," Transportation Science, Vol. 3, No. 1, 1969.

37. Newell, G. F., and Osuna, E. G. "Properties of Vehicle-Actuated Signals: II. Two-Way Streets," Transportation Science, Vol. 3, No. 2, 1969.

38. Ohno, Katsuhisa "Computational Algorithm for a Fixed Cycle Traffic Signal and New Approximate Expressions for Average Delay," Transportation Science, Vol. 12, pp.29-47, 1978.

39. Papapanou, Paraskevi P. "Analysis of Operating Parameters for Arterial Traffic Control Systems," Ph.D. Dissertation, University of Florida, Florida, 1976.

40. Pignataro, Louis J. "Traffic Engineering, Theory and Practice," Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1973.

41. Pinnell, C., Deshazo, Jr., J. J., and Wilshive, R. L. "Areawide Traffic Control Systems," Traffic Engineering, Vol. 45, No. 4, Washington, D.C., pp.20-26, 1975.

42. Prevedouros, Pano D., and Jovanis, Paul P. "Validation of Saturation Flows and Progression Factors for Traffic Actuated Signals," presented at the 67th Annual Meeting of the Transportation Research Board, Washington, D.C., 1988.

43. Riddle, R. M., and Hazzard, M. G. "Control Strategy Applications for Improving Safety on Arterial Systems," Report No. FHWA-RD-79-29, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1979.

44. Rioux, T. W., and Lee, C. E. "TEXAS: Microscopic Traffic Simulation Package for Isolated Intersection," presented at the 56th Annual Meeting of the Transportation Research Board, Washington, D.C., 1977.

45. Robertson, D. I. "TRANSYT: A Traffic Network Study Tool," Transportation and Road Research Laboratory Supplementary Report 253, England, 1969.

46. Robertson, D. I., and Gower, P. "User Guide to TRANSYT Version 6," Transportation and Road Research Laboratory Supplementary Report 255, Crowthorne, 1977.

47. Robertson, D. I. "Research on the TRANSYT and SCOOT Methods of Signal Coordination," Traffic Engineering, Vol. 56, No. 1, Washington, D.C., pp.36-40, 1986.

48. Ross, Sheldon M. "Introduction to Probability Models," 3rd Edition, Academic Press, Inc., New York, 1985.

49. Ross, Sheldon M. "Stochastic Processes," Wiley, Inc., New York, 1983.

50. Rouphail, Nagui M. "Estimating the Effect of Arterial Signal Progression on DElays: an Analytical Approach," The University of Illinois, Chicago, Illinois, 1987.

51. "SIGOP-III User's Manual," Report No. FHWA-IP-82-19, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1983.

52. "SOAP84 User's Manual," Report No. FHWA-IP-85-7, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1984.

53. Staniewicz, James M., and Levinson, Herbert S. "Signal Delay with Platoon Arrivals," presented at the 64th Annual Meeting of the Transportation Research Board, Washington, D.C., 1985.

54. "Traffic Control Systems Handbook," Report No. FHWA-IP-85-11, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1985.

55. Wagner, Harvey M. "Principles of Operations Research With Applications to Managerial Decisions," Prentice-Hall Inc., Englewood Cliffs, New Jersey, 1972.

56. Wallace, C. E., Courage, K. G., Reaves, D. P., Schoene, G. W., and Euler, G. W. "TRANSYT-7F User's Manual, Release 5," Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1987.

57. Webster, F. V., and Cobbe, B. M. "Traffic Signals," Road Research Technical Paper, No. 56, London, 1966.

58. Webster, F. V. "Traffic Signal Settings," Road Research Technical Paper, No. 39, London, 1958.

59. Yagoda, H. N., Principe, E. H., Vick, C. E., and Leonard, B. "Subdivision of Signal Systems into Control Areas," Traffic Engineering, Vol. 43, No. 12, Washington, D.C., pp.42-46, 1973.

BIOGRAPHICAL SKETCH

John Zenyoung Luh was born in the City of Taipei, Taiwan, Republic of China, on August 17, 1952. In June, 1975, he received his Bachelor of Sciences from the Department of Mathematical Sciences, National Chengchi University, graduating second in a class of 29. He was awarded the Nation Vice-President's Scholarship and Excellent Scholarship Prize.

Subsequently, he was commissioned a Second Lieutenant in the Republic of China Army. Upon release from the Army in 1977, he enrolled at the National Taiwan University where he studied Civil Engineering, specializing in transportation. During his studies, he passed the Government Examination as a recommended rank statistician. He was awarded the Master of Science degree in June, 1979.

Following graduation, he accepted a position as a traffic engineer at the Taiwan Highway Bureau. A large part of his effort involved intersection channelization, and identification and improvement of high accident locations on highways. During this work, he received a year of night-time intensive training in computer applications at the Institute for Information Industry.

In 1982, he transferred to the Computer Center at the Council for Economic Planning and Development of the Executive Yuan (Cabinet). He was in charge of managing computer facilities, developing application systems, and planning and presenting short courses on software applications. In the last year before he left, he assisted the Director in planning a major expansion of the Computer Center.

In August, 1985, Mr. Luh arrived in Gainesville and continued his studies in transportation and traffic engineering at the University of Florida, where he pursued the degree of Doctor of Philosophy in civil engineering. During the course of his studies, he was engaged in a number of traffic signal control projects as well as the technical support and software maintenance for the Federal Highway Administration's Highway Capacity Software. He has authored and co-authored a number of articles dealing with traffic signal control and highway capacity analysis.

He was awarded the University of Florida President's Recognition Award, the University of Florida Outstanding Minority Leadership Award, and the University of Florida College of Engineering Outstanding Service Award. He won the Annual Florida Section Institute of Transportation Engineers Student Paper Award two years in a row.

Mr. Luh is married to Tracy Yuiying and has two sons, Anthony and Daniel. He is a member of the Institute of Transportation Engineers, the American Society of Civil Engineers, the Transportation Research Board, the China Road Federation, the Tau Beta Pi Honor Engineering Society, the Epsilon Lambda Chi Engineering Leadership Circle, and the Phi Beta Delta Honor Society for International Scholars.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Kenneth G. Courage, Chairman
Professor of Civil Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Charles E. Wallace
Engineer of Civil Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Joseph A. Wattleworth
Professor of Civil Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Mark Chao-Keun Yang
Professor of Statistics

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Chung-Yee Lee

Chung-Yee Lee
Assistant Professor of Industrial
and Systems Engineering

This dissertation was submitted to the Graduate Faculty of the College of Engineering and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

May, 1989

Robert A. Bari

Dean, College of Engineering

Dean, Graduate School

UNIVERSITY OF FLORIDA
3 1262 08553 6646